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PYROXENES OF COMMON MAFIC MAGMAS[1,2]. PART 1

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ABSTRACT

The pyroxenes of fine grained and coarse grained mafic intrusives and those of mafic extrusives are described. Hypotheses on the trend of crystallization of pyroxenes from basalts are reviewed. The investigation indicates that augite does not grade into pigeonite, but that pigeonite is a definite and distinct mineral variety. Augite and pigeonite may and do crystallize together in equilibrium with each other. Limited, rather than complete, solid solution exists in a portion of the clinopyroxene field. Pigeonite inverts on slow cooling to hypersthene and this inversion may be used as a point on a geological thermometer. Hypersthene inverted from pigeonite can be distinguished from hypersthene of primary crystallization. The temperature of basaltic intrusions does not exceed 1140° C. and normally is close to 1120° C.

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During a period of several years data have been collected on the chemical composition of pyroxenes, their optical properties, and the relations of pyroxenes to each other in a given specimen and in suites of specimens from the same occurrence. Though the primary purpose of this study

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[1] Princeton investigations of rock forming minerals, No. 3.

[2] Presented before the Section of Volcanology, *Am. Geophys. Union*, April 1940.

was to correlate optical properties and chemical composition, certain interesting by-products resulted which are set forth in this paper.[3]

So far as the pyroxenes themselves are concerned only the common varieties have been investigated, those essentially composed of the Wo-En-Fs molecules with small to moderate amounts of trivalent oxides and titanium. Alkali pyroxenes, such as those with a considerable content of the acmite or jadeite molecule, have not been studied. The pyroxenes investigated all come from common igneous rocks—gabbros, norites, pyroxenites, diabases, basalts, andesites, etc.,—but not from such rocks as the lamprophyre dikes or markedly alkalic rock types. Broadly it might be said that this is a study of pyroxenes from normal basaltic magmas and their immediate products of differentiation, though it is quite possible that a few of the rocks considered are not differentiates of basalt.

Nomenclature for Common Clinopyroxenes

Before the clinopyroxenes can be discussed some agreement is desirable concerning a nomenclature for them. At present there is much confusion as to the meaning of such frequently used terms as augite, pigeonite, diopside, etc., and the literature is replete with obsolete and ill-defined varietal names, the majority of which might with advantage be discarded and forgotten because they introduce wholly unnecessary complications. Aside from inadequate chemical and optical data on common clinopyroxenes, the confusion in nomenclature has been the greatest obstacle in the way of an understanding of the petrological relations of igneous pyroxenes to the rocks in which they occur and the magmas from which they were derived.

An attempt will be made here to define the common clinopyroxenes (exclusive of acmite and jadeite bearing varieties) in terms of chemical composition, following the general pattern laid down by Winchell for various mineral groups. Within this chemical classification present usage will be observed so far as is feasible, and the subdivisions between varieties will be made where possible on the basis of genetic significance.

The chemical classification for this group will be based primarily on the relative molecular percentages of Wo[4] ($CaSiO_3$), En ($MgSiO_3$), and Fs ($FeSiO_3$) contained in the pyroxene and secondarily on other constituents. Present classifications as a rule make one large subdivision of the clinopyroxenes on the basis of Al_2O_3 content, or $Al_2O_3+Fe_2O_3$ content. To use the trivalent oxide content as a primary basis for classification of clinopyroxenes is objectionable on two grounds: first because alumina is a comparatively minor constituent of the clinopyroxenes, and second because it has small effect on optical properties so that its presence or absence cannot now be determined without a chemical analysis. The latter objection is of much importance when it is considered that clinopyroxene is one of the commonest minerals of the earth's crust, and petrologists are constantly faced with the necessity of naming clinopyroxenes on the basis of optical investigations alone. From the practical point of view, disregarding the alumina content, in classifying clinopyroxenes, affects but slightly the common usage of augite now defined as an *aluminous clinopyroxene* since practically all natural clinopyroxenes falling within the Wo:En:Fs field suggested for augite in this paper are also aluminous. It does, however, restrict the use of augite to a slightly smaller field than its previous rather loose definition permitted. Pigeonites also contain trivalent oxides in about the same proportions as augites, but it is obviously advantageous to restrict the use of augite so that it will not include pigeonite. Diopside-hedenbergite clinopyroxenes, redefined here as those with Wo:En+Fs ratio near 1:1, rarely contain sufficient amounts of trivalent oxides to warrant classifying them as augite under the existing definition, so that except in rare instances there will be no conflict between the existing definition and the new one suggested here. In such rare cases where aluminian diopside-hedenbergite clinopyroxenes are encountered the writer would prefer to designate them by the above name rather than consider them augites since they depart considerably in composition from normal augites of gabbros, diabases, etc., and this departure is significant from the petrologic point of view.

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[3] Chemical and optical data to be published separately.

[4] It is not meant to infer that Wo as a wollastonite molecule exists in pyroxenes, but rather Wo, En and Fs are used in the chemical sense as in norms of rocks.

The classification of common clinopyroxenes to be used in this paper is given in the figure below. The classification is based on the proportions of Wo, En and Fs, but it is specifically understood that augites and pigeonites contain moderate amounts of trivalent oxides as well.

Augites are the common pyroxenes of diabases, gabbros, norites, etc. They normally range near Wo_{40}, but the Wo content decreases somewhat with increase in Fs so that ferroaugites lie near Wo_{30}. According to the chemical classification adopted by Wager and Deer (1939), or the optical classification now used by many petrographers, the bulk of augite and ferroaugite would be considered as pigeonite. True pigeonites, however, represent a distinct mineral species which so far as is now known in all cases lies close to Wo_9. The fact that pigeonite and augite or ferroaugite may crystallize together[5] and in equilibrium in an igneous rock necessitates the limiting of pigeonite to the variety with a calcium silicate content of Wo_9 ($2V=0$ to a maximum of $<32°$, augite and ferroaugite $2V>32°$) rather than some arbitrary limit which would include part of augite and ferroaugite. The actual limits in Wo for pigeonite here suggested are Wo_5 to Wo_{15}, to allow for possible variations not at present known.

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[5] Discussed in a later part of this paper.

The diopside-hedenbergite series is split into four parts based on Mg:Fe ratio. Salite and ferrosalite are inserted between the two end members. Salite is used in this sense by Winchell. The original salite from Sala, Sweden, however, would be classed as a diopside in this report because of its relatively high $CaMgSi_2O_6$ content. Salite has also been used to refer to clinopyroxenes with a basal parting ("salite parting"). The majority of natural occurrences of the diopside-hedenbergite pyroxenes are from contact metamorphic rocks and from veins. These crystallize at a considerable lower temperature than most igneous clinopyroxenes. In general (but with certain exceptions noted in the text) the Wo content decreases with increase in temperature of crystallization. The boundary, therefore, between salite and augite is placed at Wo_{45} because most augites in igneous rocks contain less calcium silicate than Wo_{45}, and most contact metamorphic and vein salites more calcium silicate than Wo_{45}.

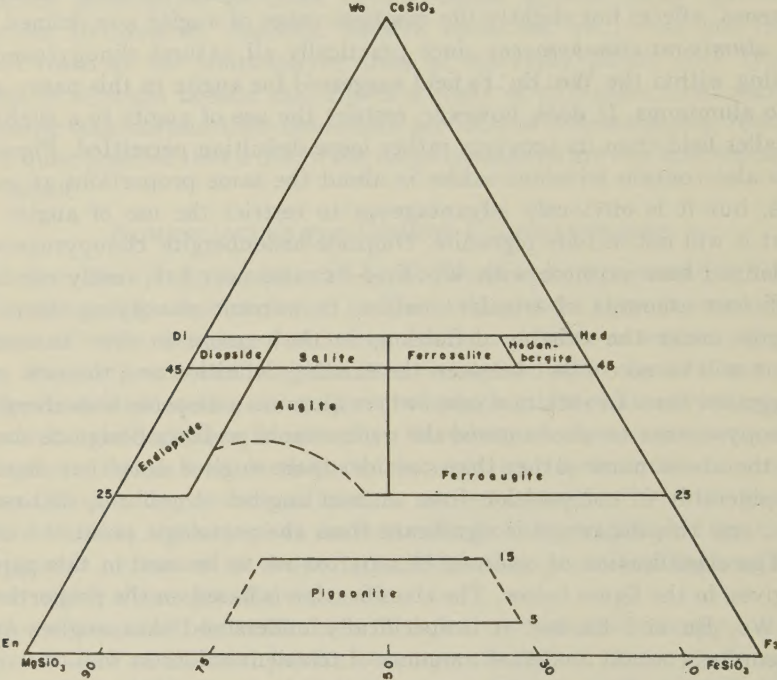

FIG. 1

The remaining clinopyroxenes lie on either side of the diopside field.

For those below diopside, towards enstatite the name endiopside is given, a contraction of Wahl's little used enstatite-diopside. Pyroxenes in this field are rare but of sufficient genetic significance to warrant a distinctive name. All examples thus far examined by the writer contain substantial amounts of Cr_2O_3 (about 1 per cent). No name is given to those clinopyroxenes above the diopside field (containing excess $CaSiO_3$). As a rule these clinopyroxenes are also rich in TiO_2 and Al_2O_3 so it is questionable whether they can be dealt with in a classification based primarily on Wo:En:Fs ratios. Winchell[6] suggests the presence of a $CaTiAl_2O_6$ molecule to account for these pyroxenes. It may be noted also that Barth (1931A) suggested the presence of this molecule and synthesized clinopyroxenes with up to ten per cent of the $CaMgTi_2O_6$ molecule in combination with diopside. In this latter case the Ti was considered to have replaced Si in the lattice rather than Mg as in the molecule given above.

To take care of certain varieties containing more than ordinary amounts of one of the nonessential elements, such terms as titanaugite, chrome-diopside, manganhedenbergite might be adopted from present common usage, or, if preferable, the adjectival forms suggested by the committee on nomenclature such as *manganoan* hedenbergite might be used.

As shown in Fig. 1 by dashed rather than solid lines, some of the composition limits of the various clinopyroxenes are left indefinite. No doubt as additional chemical data becomes available, modifications in the present classification will be necessary. A considerable portion of the entire field has been left blank. It is probable that further investigations will bring to light pyroxenes in some of these areas, but others are probably fields in which no natural clinopyroxenes will be found.

PIGEONITE-AUGITE RELATIONS

Pigeonite was defined by Winchell (1900) as a clinopyroxene with a small optic angle. It is redefined in this paper in terms of composition, but clinopyroxenes within the composition field of the definition have small optic angles, and all common clinopyroxenes of igneous rocks which lie outside of this field have larger optic angles so that the essential feature of Winchell's definition has been retained.

It is generally considered that a complete gradation from clinopyroxenes of pigeonitic composition to augites exists;[7] assuming for the moment that such a gradation does occur, it would be convenient to place some upper limit on the optic angle of pigeonite above which value the pyroxenes would be considered to be augites. The writer suggests that a convenient limit would be 2V = 32° in the plane parallel to (010). Those clinopyroxenes with the optic plane perpendicular to (010) are definitely pigeonites and the optic angles of these probably do not exceed 32°. The great majority of pigeonites in igneous rocks seem to have their optic plane perpendicular to (010). The orientation of the optic plane is often not given in the more recent literature.

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[6] Personal communication.

[7] Laboratory investigation of pyroxenes shows a solid solution series with a minimum for the system clinoenstatite-diopside (Bowen) and also a similar series for hedenbergite with clinoferrosilite (Bowen, Schairer and Posnjak), but pyroxenes intermediate between

In actual observations of optic angles on augites and pigeonites (excluding phenocrysts)[8] from the same rock, a well defined gap appears to exist. The writer has examined a large number of such slides of rocks from various parts of the world. In practically all of them there is a gap in optic angle values between approximately 2V = 30° and 2V = 40°. In a few cases augites with optic angles slightly below 40°, or pigeonites with optic angles slightly above 30°, were found. The normal optic angle range for augites is from 40° to 52° and the average about 46°.[9] In the case of pigeonite the optic angle varies much more rapidly with change of composition (Wo content). The optic angles commonly range from 2V = 30°? parallel to (010) through 2V = 0° to 2V = 30° perpendicular to (010). The average values would lie between 2V = 0° and 2V = 25° $\perp$ to (010).

It is quite likely that the gap mentioned above might be shifted a few degrees one way or the other, or narrowed by the effects of non-essential minor constituents present in highly variable amounts in clinopyroxenes. Titanium is perhaps the most important of these.[10]

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these two systems have not been investigated. Because of the laboratory data it has generally been assumed that a complete series of solid solutions existed between augite and pigeonite.

[8] In this entire discussion phenocrysts are excluded from consideration since they are commonly of abnormal composition. This will be considered separately when the pyroxenes of effusives are taken up. The clinopyroxenes here under consideration are those of even grained rocks such as diabases or dolerites and the groundmass pyroxenes of such porphyritic rocks as basalts and andesites. The optic angles of the so called "augite" phenocrysts commonly lie between 55° and 60°.

[9] Optic angles of augites which have cooled slowly and thus exsolved hypersthene as fine lamellae will be higher than those in the more rapidly cooled rocks—45° to 60°. Essentially the clinopyroxene host is changed in composition from augite towards a diopside-hedenbergite pyroxene and will have comparable optical properties. The bulk composition of this clinopyroxene plus its lamellæ will, of course, be the same as that of the original augite.

[10] Most optic angle measurements are subject to an error of ±1°. In some of the older references errors as high as 5° might be expected. Determinative errors will, therefore, tend to make the optic angle gap less well defined.

Examples of the occurrence of two clinopyroxenes in a single rock and of specific observations on optic angles of the two clinopyroxenes as made by various investigators, are given below. It is very common in the literature to find statements that the groundmass pyroxene of a basalt, or an andesite, has a highly variable optic angle, ranging continuously from 2V = ±50° to 2V = 0°. Kuno (1936A) makes the following comment on the groundmass pyroxenes from andesites of the Hakone volcano, Japan: " . . . it is noted that the optical data of the groundmass *pigeonites* show that they tend to group in two types, viz., *pigeonite* with 2*V* nearly 0° and that with 2V nearly 40°.[11] But since intermediate types are occasionally found, the above fact does not mean existence of miscibility limits in the composition range of pigeonite." As can be noted below *some* intermediate values are found but the actual observations themselves suggest that *all* intermediate values are not found.

Actual observations made by Kuno on andesites from Hakone volcano are as follows:

GROUNDMASS PYROXENES

Rock No. 1. 2V = 0° to very small angles.
Rock No. 2. Pyroxene not reported.
Rock No. 3. $\left\{\begin{array}{l}\text{Type 1 } 2V \doteqdot 43^\circ \\ \text{Type 2 } 2V \doteqdot 0^\circ\end{array}\right\}$ nearly equal amounts of 1 and 2.
Rock No. 4. $\left\{\begin{array}{l}2V = 43^\circ,\ 39^\circ \\ 2V = 29^\circ\end{array}\right\}$ observations on three random grains. Some nearly uniaxial grains also present.
Rock No. 5. Augite 2V = 46°, and a little nearly uniaxial pigeonite present.
Rock No. 6. $\left\{\begin{array}{l}\text{Type 1 } 2V = 49^\circ - 42^\circ \\ \text{Type 2 } 2V \doteqdot 0^\circ\end{array}\right.$

ZONED PHENOCRYSTS

Rock No. 1. Augite 2V = 49° − 46°.
Rock No. 2. Augite 2V = 52° − 48° core; 41° margin.
Rock No. 3. Augite 2V = 50° − 48° core; 42° margin.
Rock No. 4. Augite 2V = 51° − 49° core; 39° margin.

	core	margin
crystal *a*	2V 49°	39°
crystal *b*	2V 49°	44°
crystal *c*	2V 51°	42°
crystal *d*	2V 51°	
crystal *e*	2V 50°	
crystal *f*	2V 49°	

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[11] The augite of this paper.

Rock No. 5. (1) Pigeonite 2V = 17° − 10° core, *sharply defined* marginal zone 2V = 48°.

	core	margin
crystal *a*	2V = 10°	2V = 47°
crystal *b*	2V = 12°	2V = 49°
crystal *c*	2V = 16°	2V ca45°
crystal *d*	2V = 17°	2V ca45°
crystal *e*	2V = 13°	

(2) Augite 2V = 48° − 43° core; 2V = 47° − 43° margin.

	core	margin
crystal *a*	2V = 45°	47°
crystal *b*	2V = 45°	44°
crystal *c*	2V = 44°	43°
crystal *d*	2V = 47°	44°

Rock No. 6. Pigeonite 2V ≑ 0°.
Augite 2V = 47° core, 2V = 46° margin.
Kuno (1940) groundmass pyroxenes, Hakone volcano.
Type (1) 2V = 44° − 36°.
Type (2) 2V ≑ 0°.

In the above observations it can be noted that no optic angle values between 2V = 29° and 2V = 36° are given. Furthermore, excluding one measurement of 2V = 36° and one measurement of 2V = 29°, there are then no values between 2V = 17° and 2V = 39°. Thus out of forty-six specific observations thirty-four fall between 52° and 39° and ten between 17° and 0°.

In the following twelve papers two clinopyroxenes (excluding phenocrysts) are present in the rocks described and are clearly so recognized by the authors.

(1) Cohen (1887) found two clinopyroxenes in a diabase from Richmond, Cape Colony. The following optic angle values are reported (converted by present writer from 2E to 2V) $8\frac{1}{4}$°, 10°, 12°, $13\frac{1}{2}$°, 15°, $18\frac{1}{2}$°, and for a second pyroxene $44\frac{1}{2}$°.

(2) Hovey (1892) examined a diabase near Rio de Janeiro, reporting two clinopyroxenes, the optic angle for one 2V = $21\frac{1}{2}$° and 19°, and for the other $46\frac{1}{2}$°.

(3) Hovey also describes two clinopyroxenes in the Halleberg diabase, Sweden, and gives the optic angle for one, 2V = 21°.

(4) Backlund (1907)[*] found two clinopyroxenes in the same diabase, for one 2V = $15\frac{1}{2}$° ⊥ to (010), and for the other 2V = 57° or less parallel to (010).

(5) Pirsson (1898) writes of two clinopyroxenes, previously analyzed by Hawes, in the West Rock, New Haven, diabase. Optic angle measurements on these pyroxenes by the

[*] Since compiling these data the writer finds that Backlund described two clinopyroxenes in a large number of diabases from Spitzbergen, King Charles, Land, and Xiririca (Brazil), Halle-Hunneberg and Köpalla (Sweden), and Anabar (Siberia).

writer gave for one 2V = 44½°, 48°, 49°, and several near 45°, and for the other 2V = 22°, 21°, 20°, 15°, 14°, 12½°, and a number between 10°–0°, optic plane perpendicular to (010).

(6) Wahl (1907) notes two clinopyroxenes in several diabases, that at Pierri-Perävaara, Karelia, gave 2V = 38½° for one and 2V = 18° for the other (as converted from 2E by the writer).

(7) Asklund (1925) found a little clinopyroxene with an optic angle near 0° surrounding hypersthene, and a second clinopyroxene described as diallage-like augite in a noritic gabbro from Stavsjö, Sweden.

(8) Gillson (1926) notes two clinopyroxenes in the Westfield, Massachusetts, diabase. Two optical angle measurements on one of these gave 2V = 10°54′ and 24°16′. The other has a 2V about 60° (evidently not measured).

(9) Holmes and Harwood (1928) find two clinopyroxenes in many of the Whin Sill rocks, one of these, the dominant pyroxene, has an optic angle near 50° and the other is in all cases near 0°.

(10) Tyrrell and Sandford (1934) note a purplish brown augite and a colorless clinopyroxene which is virtually uniaxial in gabbroic rocks from Spitzbergen.

(11) Bugge (1940) describes a pigeonite with 2V = 16°, optic plane parallel to (010), and an augite with 2V = 52° in a hyperite from the Arendal district of Norway.

(12) Walker (1940) writes of pigeonite and augite in a number of specimens from the Palisades diabase. Measurements in one such specimen by the present writer gave for one pyroxene 2V = 42°, 43°, 44°, 44°, 46°, 47°, 48°, and 49°, and for the other 2V = 12°, 15°, 17°, 22° and 23°, optic plane perpendicular to (010).

In two other papers there can be no doubt of the presence of two clinopyroxenes from the descriptions given but the authors do not specifically so state. Benson (1916) makes the following comment with regard to the clinopyroxenes of an Antarctic dolerite: "In the same slide crystals may occur the optic angles of which vary from 90° to 0° (2E). The most frequent values are those lying between 0° and 30° and from 65° to 90°." (Estimated 2Vs by the writer 38° to 50° and 0° to 17°.) Bogue and Hodge (1940) examined Cascade andesites from Oregon and found that the groundmass pyroxenes were "pigeonites," but the optic angle values as recorded on a graph are as follows: 2V = 49°, 49°, 48°, 48°, 46°, 45°, 44°, 43°, 42°, 42°, 40°, 40°, 36°, 35°, and 2V = 26°, 22°, and 20°.

The optic angle measurements above can be considered a fairly representative random sample. If all of these be plotted on a frequency of occurrence curve as Fig. 2A, the gap in values is evident. Even if the gap were not present on this curve (as a result perhaps of both the effect of minor constituents and small observational errors), the two well marked peaks on the curve would cast doubt on the assumption that a complete series of clinopyroxenes from augite to pigeonite exists. The two peaks suggest the presence of two distinct solid phases each of which is somewhat variable in composition. Considering those optic angles of pigeonites which lie in the plane ⊥ to (010), the gap becomes even more evident since they should be regarded as being less than 0° (Fig. 2B). The orientation of the optic plane was disregarded in making the upper diagram (Fig. 2A) since this orientation is not given in many of the papers cited. Almost all of the pigeonites examined by the writer have their optic plane perpendicular to (010).

A detailed discussion of zoned relations of clinopyroxenes in some of the above rocks would lead to similar conclusions. Crystals having augite cores (2V = ±45°) and pigeonite borders (2V = ±0°) are commonly pointed to as indications of a complete series of solid solutions. In all cases examined by the writer and in accurate descriptions in the literature there is a sharp boundary between the augite and pigeonite of these crystals and a gap in optic angle values, just as found in the analysis of the previous paragraphs. It may be mentioned that, though less common, pigeonites with augite borders are also found. The comparative rarity of the latter might be ascribed to the fact that the majority of normal mafic magmas lie in the field which crystallizes augite first (on the augite side of Tsuboi's two pyroxene boundary).

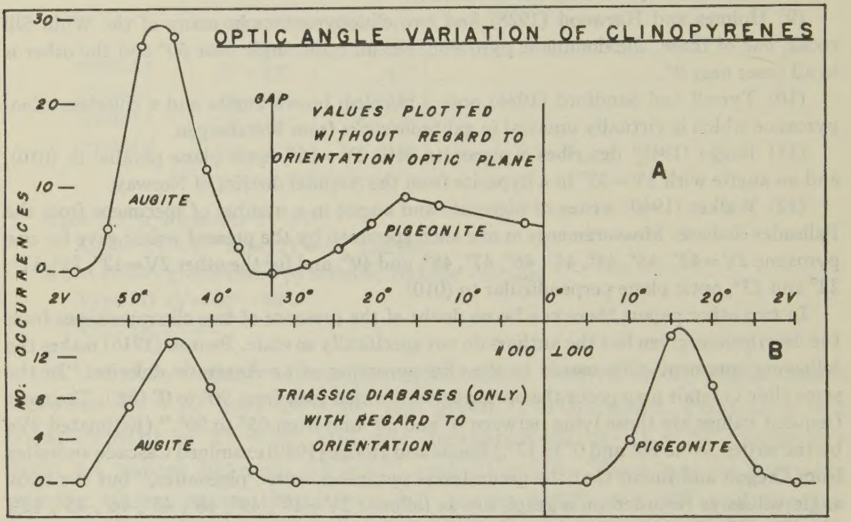

FIG. 2. (A and B)

In each of the occurrences described above pigeonite was accompanied by augite. In all rocks examined by the writer this was also true. Several cases were noted in the literature in which pigeonite was said to be present in the rock, but augite was not specifically mentioned as accompanying it. These are the chemically analyzed specimens from Pigeon Point, mentioned by Winchell (1900), Washington's Deccan trap pyroxene, Doelter's (1882) Cape Verde Island groundmass pyroxene, and the Fölgö and Onega pigeonites of Wahl (1907). In all of these cases, however, the analyses themselves suggest a mixture of augite plus pigeonite (see discussion of chemical composition of pigeonite).

Thus two general conclusions may be drawn from the above discussion of pigeonite.

Conclusion 1. Limited, not complete, solid solution is the rule for natural clinopyroxenes intermediate between the diopside-hedenbergite series and the clinoenstatite-clinoferrosilite series for a large part of the whole composition field enclosed by the above end-members.

Conclusion 2. Pigeonite is accompanied by augite in most if not all natural occurrences. An exceptional case might be postulated where pigeonite was the first of the two clinopyroxenes to crystallize and the magma was completely solidified (as for example by chilling to a glass) before the second clinopyroxene, augite, appeared.

Pyroxenes of Diabases and Dolerites

The most ideal rock types in which to investigate pyroxenes and pyroxene relations of mafic magmas are the diabases and dolerites. The groundmass of basalts is, as a rule, difficult to study because of the small grain size and the phenocrysts are commonly of abnormal composition, as will be shown later in the discussion. Other disadvantages inherent in the study of effusives are the complexities resulting from non-equilibrium conditions caused both by rapid chilling at the surface and by rapid rises in temperature produced by oxidation. With due regard for these complexities it can be shown that crystallization of basalt follows the same pattern as for intrusive diabase and dolerite, with minor modifications in one direction or another resulting from a rapidly varying environment and imperfect equilibrium conditions. In the coarser grained, more slowly cooled gabbroic or noritic intrusions the course of pyroxene crystallization is the same as in diabase and dolerite, but because of almost perfect equilibrium conditions certain less stable, transitional, phases are completely absent in the final rock products, thus making them less easily susceptible to interpretation.

A. Triassic Diabases of New Jersey

The first pyroxene to separate from the Palisades-Rocky Hill Sill and the sill south of Lambertville appears to be a normal augite ($2V = 45° \pm 5°$). It occurs in the chilled border facies as glomero-porphyritic aggregates of microphenocrysts. A little olivine accompanies or may slightly precede it. The groundmass contains pigeonite and augite, with pigeonite in excess. Immediately above the lower chilled border facies at Lambertville and in the Palisades, hypersthene appears as fairly large ophitic crystals, accompanied by augite. About twenty per cent of olivine is present in this zone in the Palisades—the well-known olivine layer—

and less olivine is present at Lambertville. At Rocky Hill this development of a marked melanocratic layer has not been observed. It may be noted that the hypersthene is of the clear, slightly pleochroic variety with no exsolution lamellae. Proceeding upwards in these sills the olivine disappears and both pyroxenes become more iron-rich (indices of refraction increase). The first evident change to be noted is the appearance of hypersthene with rather irregular oriented plates or rows of globules of exsolved augite. The change takes place when the hypersthene reaches a MgO:FeO molecular ratio of approximately 7:3. All hypersthenes more iron-rich than this 7:3 ratio exhibit the roughly oriented inclusions. In specimens taken from the level at which the change occurs individual crystals may be seen with cores of clear hypersthene and border zones of slightly more iron-rich hypersthene containing the inclusions. At a higher level in the Palisades sill, orthopyroxene disappears entirely, but its place is evidently taken by pigeonite ($2V = 0° - 25°$, optic plane $\perp$ to (010)). The augite continues to crystallize as before. At this level the rock resembles the West Rock, New Haven, occurrence described by Pirsson (1898), except that both the augite and pigeonite have a faintly brownish color. In the West Rock occurrence the pigeonite is colorless and has a characteristic type of alteration so that the two clinopyroxenes are easily distinguished, but in the Palisades they can only be distinguished by the differences in their optic angles (see measurements on a previous page). In the most iron-rich differentiates of the New Jersey diabases, pigeonite disappears and only ferroaugite remains. Phillips' (1899) two analyses of clinopyroxenes from the Rocky Hill diabase were both taken from such late ferriferous differentiates.

The augites, though free of exsolution lamellae in the more quickly cooled facies, commonly exhibit exsolved hypersthene as lamellae parallel to (100) in the more magnesian varieties, and parallel to (001) in the more ferriferous. They also show in some cases an alteration which appears to be identical with that described by Krokström (1932, p. 279) for the Breven dolerite.

B. Karroo Dolerite, Downes Mountain

A Karroo Sill has recently been described in some detail by Walker and Poldervaat (1941). The pyroxene relations are remarkably similar to those described for the New Jersey Triassic diabases with one notable exception, namely, that orthopyroxene is the first pyroxene to crystallize rather than augite.

The crystallization sequence of the pyroxenes is summarized below:

1. Earliest pyroxene, orthorhombic, bronzite En_{83}, followed after a short interval by augite.

2. More iron-rich, hypersthene with oriented plates of augite which is accompanied by augite.

3. In the upper part of the sill the place of orthopyroxene is taken by pigeonite 2V=0°–12°; augite is still present. (An "antipathic relationship" of orthopyroxene to pigeonite is pointed out.)

4. The late stage pyroxene mentioned is called a "hypersthene augite" which appears to be the ferroaugite of this paper (or an augite very near the ferroaugite boundary). From the optic angle values given it seems probable that a little pigeonite is also present, but that the ferroaugite and the pigeonite are so similar that no distinction was made between the two (2V=20°–45°).

5. In the final stage of crystallization a pegmatitic facies was developed which contains a much altered clinopyroxene. From the description given and by analogy with the Palisades diabase, this is a ferroaugite.

Certain interesting relationships are observed on individual pyroxene crystals. Pigeonites are described which have a shell of augite surrounding them in optical continuity. The boundary between the two phases is distinct and sharp. Optical angle measurements on several such grains are given as follows:

Core 2V=0°, 0°, 3°, 5°, 11°, 12°, 12° (=pigeonite).

Shell 2V=43°, 40°, 39°, 38, °34°, 34°, 31° (=augite).

A gap in values between 31° and 12° may be noted. Aside from one augite with an optic angle value of 31°, all readings fall within the optic angle ranges for augite and pigeonite as given in this paper. As suggested previously the 31° value (which is 1° lower than the division point given) may be the result of the presence of some minor constituent in more than normal amount, or may be due to a small observational error.

It is also interesting to note that in this sill (where orthopyroxene has been demonstrated to have crystallized first) pigeonite crystals have a shell of augite around them, rather than the reverse relationship which is so common in those magmas which have crystallized augite first.

Cases are also noted where augite formed a shell around the hypersthene which contains oriented plates of augite, the hypersthene being present instead of the pigeonite as described above.

From the index of refraction values given by Walker and Poldervaat it appears that the change from normal orthopyroxene to orthopyroxene with oriented plates of augite took place at a MgO:FeO molecular ratio of 73:27 (±3), which is consistent with the values found in a number of other mafic intrusives.

C. Whin Sill and Related Dikes

From Teall (1884) and the more recent study of Holmes and Harwood

(1928), the pyroxene relations in this suite of mafic intrusives can be worked out. The same phases appear to be present as were described in the New Jersey diabases.

The following pyroxenes are described by Holmes and Harwood:

(1) Hypersthene
(2) Hypersthene with "strips" of monoclinic pyroxene
(3) Pigeonite 2V ≑ 0°.
(4) Augite 2V ≑ 50°. "The dominant pyroxene."

Holmes and Harwood state that: "we do not understand how it is that hypersthene is the dominant magnesian pyroxene (*in some rocks*) whereas in others its place is largely taken by A (*pigeonite*), but it is clear that the two are mutually complementary. . . . " Hypersthene is conspicuous in the northern occurrences where pigeonite is lacking, and pigeonite is commonly present in the southern part of the area where hypersthene is absent. The analyzed rock 572, Grassless Burn, Elsdon, however, has three pyroxenes. A little hypersthene is enclosed in nearly uniaxial augite (*pigeonite*), and ordinary augite is also present. In the more ferriferous facies, such as in Teall's Chaldron Snout, "coarse veins," analyzed specimen, and in the Tyne Head analyzed specimen only one pyroxene is present: augite or ferroaugite.

There is a slight suggestion in Holmes' description that the hypersthene starts to crystallize ahead of the augite, but this point is not at all clear. The normative molecular ratio of Wo:En:Fs is such, that it appears to lie very close to, or just above (on the augite side of) the two pyroxene boundary. In all other respects, if not in this respect, the crystallization of the Whin Sill pyroxenes is the same as in the Triassic diabases.

D. Diabasic Border Facies of the Stillwater Complex.

The fine grained border facies of the Stillwater Complex has a subophitic texture with hypersthene greatly in excess of augite. The hypersthene is relatively iron-rich (MgO:FeO = 56:44), and it contains roughly oriented inclusions of augite as plates. The textural relations indicate crystallization of the lime-poor pyroxene* first, followed by crystallization of both lime-poor pyroxene and augite together.

Igneous rocks of basaltic composition which show crystallization of lime-poor pyroxene before augite are exceedingly rare. It seems likely that in most cases olivine will crystallize in such rocks rather than a lime-poor pyroxene. In magmas of less mafic composition (andesitic) the crystallization of a lime-poor pyroxene first, in place of augite, is fairly common. The majority of the Japanese andesitic magma products show a lime-poor pyroxene crystallizing before augite and many of the Lesser Antilles magmas have the same characteristic.

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* Lime poor pyroxene = pigeonite or orthopyroxene.

E. Summary of Pyroxene Relations in Diabases and Dolerites.

1. Augite normally crystallizes first, but in rare cases a lime-poor pyroxene may separate ahead of the augite.
2. Shortly after the appearance of the first pyroxene it is joined by the second, and the two crystallize together for the greater part of the crystallization history of the intrusive.
3. Hypersthene changes abruptly to hypersthene with oriented plates or rows of globules after a certain MgO:FeO molecular ratio is reached (near 70:30).
4. Hypersthene with oriented inclusions gives way to pigeonite as the crystals become still more iron-rich, pigeonite and augite separating simultaneously during this portion of the crystallization history.
5. Pigeonite ceases to crystallize after reaching a MgO:FeO ratio near 35:65 and ferroaugite continues alone.

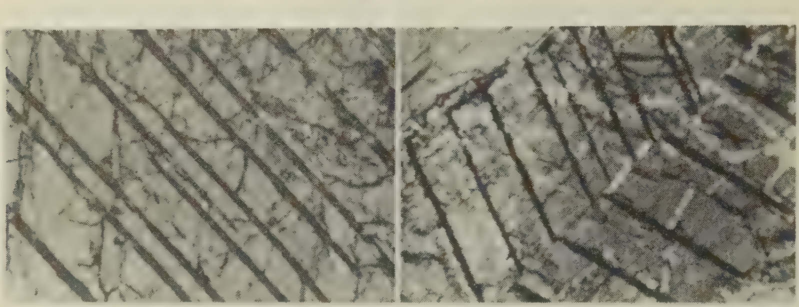
PYROXENES OF COARSE GRAINED MAFIC INTRUSIVES, NORITES AND GABBROS

A. Stillwater Complex, Montana

In this sheet-like complex the writer has collected a series of specimens from the floor upwards, and inasmuch as this intrusive has been built up by settling of crystals layer upon layer, it is possible to study not only the relations of the pyroxenes to each other and to plagioclase in individual specimens, but also to observe changes which occur as crystallization proceeds.

The first ferromagnesian mineral to appear in the course of crystallization of the Stillwater magma is a magnesian olivine. It is soon followed and its place taken by an orthopyroxene, bronzite, with a MgO:FeO molecular ratio of approximately 86:14. As crystallization proceeds the MgO:FeO ratio gradually decreases. These orthopyroxenes contain roughly five molecular per cent of Wo component which exsolves from them in fine diopsidic lamellae parallel to (100) with slow cooling, as described by the present writer and Phillips (1938 and 1940). Associated with the earliest orthopyroxene rocks is a bright green chrome-endiopside, found in small amounts. It is completely interstitial to the bronzite and evidently crystallized from the liquid between the settled euhedral crystals of bronzite.

With continued crystallization the clinopyroxene changes in color from bright green to the normal dark green of augite. It is still present in very small amounts. After the orthopyroxene reaches a MgO:FeO molecular ratio of 80:20, abundant clinopyroxene appears as settled crystals separating contemporaneously with hypersthene. The two pyroxenes continue to crystallize simultaneously from this level in the complex upwards to the highest exposure. The uppermost portion of the complex is covered so the crystallization cannot be traced to completion.



A B

FIG. 3. Oriented plates of augite in a hypersthene from the Stillwater complex.

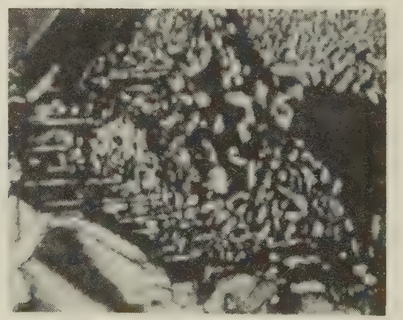


FIG. 4. Hypersthene with oriented plates of augite in the Palisades diabase. Arrangement less regular than in Fig. 3.

Where the hypersthene reaches a MgO:FeO ratio of approximately 73:27, an abrupt change takes place in it. In composition this change consists in an increase of the Wo component from five molecular per cent to nine per cent. In thin section it is evident because this orthopyroxene has plates of diopsidic clinopyroxene commonly oriented approximately parallel to what appear to be dome planes in the orthopyroxene. The fine lamellae parallel to (100) are also developed. They are offset on crossing the oriented plates in such a manner that it appears that they are younger than the plates (Fig. 3).

B. Bushveld Complex. Transvaal

The pyroxenes of the Bushveld Complex are almost identical with those described above for the Stillwater. The course of crystallization is the same and the hypersthene undergoes the same abrupt change to the variety with oriented plates at or near a MgO:FeO molecular ratio of 73:27.

C. Skaergaard Intrusion, East Greenland

The lower portion of this intrusive described by Wager and Deer (1939) is hidden so that little is known of the earlier ferromagnesian phases. The lowest exposed horizons have two pyroxenes practically identical in composition with the two pyroxenes of the uppermost exposed horizon of the Stillwater. A "border group" picrite gives some indication of the type of rock to be found in the deeper hidden portion. This rock contains an augite and a bronzite, approximately En_{80}, which shows the fine lamellae parallel to (100) as do the Stillwater and Bushveld orthopyroxenes of that composition. The next most magnesian orthopyroxene described is near En_{60} and has the oriented plates also found in all the Bushveld and Stillwater orthopyroxenes with less magnesia than En_{73}. The change from the first type to the second must therefore take place between En_{80} and En_{60}, but cannot be more precisely determined from the data given. Orthopyroxenes with oriented plates continue to be present together with augite until a composition of near En_{35} is reached. Beyond this, orthopyroxene is absent, but ferroaugite and iron-rich olivine continue to crystallize. Olivine is found through most of the exposed section of the Skaergaard, the magma being undersaturated whereas the Bushveld and Stillwater are just about saturated having neither appreciable normative olivine nor quartz.

The clinopyroxenes are most interesting in this intrusion because they range all the way from fairly magnesian augites to ferroaugites with practically no magnesia. The ferroaugites are deficient in the Wo component compared to common augites.

Table 2 (In Part 2) shows the progressive changes in pyroxenes of the Stillwater and Skaergaard intrusions as crystallization proceeds.

D. Duluth Gabbro, Minnesota

The writer has relatively less information on the pyroxenes of this intrusion. The data presented are based on a suite of some forty specimens most of which were collected by Edward Sampson in 1932.

A purplish augite is the first pyroxene to separate from the Duluth gabbro. It occurs as coarse poikilitic crystals including olivine in the peridotite near the base of the lopolith. Higher in the intrusion hypersthene appears, but it is in all cases subordinate in amount to the augite. As in the Stillwater, Skaergaard, and Bushveld it gives way to hypersthene with oriented plates as the orthopyroxene becomes more ferriferous.

Some of the specimens of this suite contain only augite or ferroaugite, and presumably hypersthene with oriented plates ceases to crystallize as in the Skaergaard intrusion. The writer is not positive that this is the case, however, since the particular specimens examined show small areas of strongly pleochroic chlorite which could possibly represent completely replaced hypersthene.

E. Summary of Pyroxene Relations in Coarse Grained Mafic Intrusives.

1. Either augite or bronzite begin to crystallize first; examples of the latter type are exceedingly rare.
2. Shortly after the first pyroxene appears, the second begins to crystallize with it.
3. If the first pyroxene is bronzite the earliest clinopyroxene is chrome-endiopside.
4. After the MgO:FeO ratio of the orthopyroxene reaches approximately 73:27, hypersthene gives way to hypersthene with oriented plates of augite.
5. Augite and hypersthene with oriented plates continue to crystallize together until a MgO:FeO ratio near 35:65 is reached.
6. Hypersthene then drops out and ferroaugite continues to crystallize until an almost pure Ca-Fe ferroaugite is reached in the final stage.
7. As compared with the fine grained intrusives the relatively longer range of crystallization of hypersthene with oriented plates may be noted, and the complementary absence of pigeonite. This is the only essential difference between the coarse grained gabbros and norites and the fine grained diabases and dolerites.

PYROXENE RELATIONS IN EFFUSIVE ROCKS, BASALTS AND ANDESITES

In the effusive rocks it is much more difficult to work out pyroxene relations, because of the small grain size of the groundmass, abnormal compositions of many phenocrysts, and the lack of differentiation exhibited by flows. It is necessary to choose favorable specimens from many parts of the world in order to get at the particular features required for an understanding of the relations. The writer is, therefore, dependent to a much larger extent on the literature supplemented by only a few personal observations.

A. Phenocrysts.

A clinopyroxene, augite or diopside, and an orthopyroxene, hypersthene, are the common pyroxene phenocrysts of mafic lavas. Either one, or, less commonly, both may be present. The hypersthene does not contain the fine exsolution lamellae parallel to (100). Hypersthene with oriented plates is not found. Pigeonite as phenocrysts is exceptionally rare (Mull and Hakone) and is limited to lavas with a low MgO: FeO ratio, as a rule (andesites). It is significant, however, that it does occur in this form.

Though in some lavas the clinopyroxene phenocrysts are comparable to the augite crystals found in diabases, gabbros, etc., it is more common to find clinopyroxenes of a diopsidic, rather than augitic composition (the Wo:En+Fs ratio is near 50:50 rather than 40:60). There are no equivalent diopsidic clinopyroxenes in the common mafic intrusives. The conclusion is that the clinopyroxene phenocrysts were normal augites in the intratelluric stage, but have for some reason been changed in composition upon approaching the surface, or after extrusion.

The change which takes place can be noted by comparing the many analyses of phenocrysts in extrusives with normal augites of moderate-depth hypabyssal to plutonic intrusives. The change is readily recognized optically by the increase in the optic angle of the clinopyroxene as the composition changes from the normal composition Wo_{40} $(En, Fs)_{60}$, $2V=47°\pm$ toward Wo_{50} $(En, Fs)_{50}$, $2V=60°\pm$.

It may also be noted that the groundmass augite of extrusives either does not take part in this change or does so to a lesser extent.

A few observations are given below to illustrate the statements made above:

1. Barth (1931) gives the compositions of phenocrysts of Pacific lavas. All of these lie near the diopside-hedenbergite line.
2. Bogue and Hodge (1940) state that optic angles for phenocrysts of Cascade lavas range from 52°–58°, plus one observation of an angle of 62°. Groundmass augites in the same rocks have optic angles averaging about $2V=43°$.
3. Examination of Triassic Watchung basalts by the writer shows that augite microphenocrysts have optic angles near $2V=52°$, whereas the groundmass augites average 3° less, and the augites of the Triassic intrusive sills average 2° less than the latter.
4. A dike extending upwards into an extrusive breccia was studied by R. Hutchinson (senior thesis, Princeton University 1941). Examination of augites in the dike some 600 feet below the original surface give

values for the optic angle averaging $55\frac{1}{2}^\circ$, whereas those in the extrusive facies are $2\frac{1}{2}^\circ$ higher.

Considerably more investigation of augites of very near surface intrusives and extrusives will be necessary to arrive at a definite conclusion as to the nature and cause of this change. It is mentioned in this report mainly to emphasize that such clinopyroxenes are abnormal in that they lie off the main trend of crystallization of augites under moderate hypabyssal to plutonic conditions. A number of chemical analyses of "augites" from mafic lavas were made by Washington. All of these are close enough to $Wo:En+Fs=50:50$ to be classed as diopsides or salites. None of them would be called "augite" as defined in this paper. Most of them have a relatively high Al_2O_3 content and a slighly more than average amount of Fe_2O_3 as compared to augites of plutonic to moderately deep hypabyssal intrusives.

At present it is difficult to account for the abnormal character of these phenocrysts. It may have something to do with oxidation occurring near or at the surface and the accompanying increase of temperature, or it may be related to low pressure, or to the action of volatiles.

B. Groundmass.

The normal groundmass pyroxenes of mafic effusives are augite and pigeonite. In the highly ferriferous extrusives ferroaugite occurs alone. The appearance of hypersthene in the groundmass in place of pigeonite is exceedingly rare, the reverse of the relations as regards the phenocrysts.

C. Summary of Pyroxene Relations in Mafic Effusives.

(1) (a) *Phenocrysts* i. Augite or diopside alone.
    ii. Augite or diopside+hypersthene.
    iii. Hypersthene alone.
    iv. Very rare—pigeonite in place of hypersthene in ii and iii above.
  (b) *Groundmass* i. Augite+pigeonite.
    ii. Ferroaugite alone.
    iii. Very rare hypersthene in place of pigeonite in i above.

(2) Hypersthene with oriented plates (or more irregular oriented inclusions) of augite is not present in extrusives,[12] but the complementary mineral, pigeonite, is common. This is the exact reverse of relations in the coarse grained intrusives where pigeonite was never present, but hypersthene with oriented plates is common. The fine grained intrusives are intermediate between the coarse grained intrusives and the effusives in that either pigeonite or hypersthene with oriented plates may be present.

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[12] One exception apparently noted by Kuno (1938).

(3) Intratelluric augite phenocrysts in many cases change towards diopside in composition during extrusion. Account must be taken of this in establishing the course of crystallization of clinopyroxenes from mafic magmas.

(4) Excluding this minor change in composition of augite phenocrysts towards diopside, the chemical composition of the pyroxene phases and the change in composition with differentiation is the same in coarse-grained intrusives, fine-grained intrusives and effusives of common mafic magmas.[13]

(To be continued)

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[13] Chemical equivalence of pigeonite and hypersthene with oriented plates is shown later in this paper.

NEPHELINE

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In 1912 Bowen[1] produced pure sodium nepheline artificially and measured its optical propoerties; he also showed that it could take into crystal solution as much as 35 per cent of the materials of anorthite; with increase in the tenor of these constituents he showed that the index, N_o, remained constant at 1.537, while N_e increased from 1.533 to 1.539, thus changing the optic sign from minus to plus. In 1917 he showed[2] that $NaAlSiO_4$ can intercrystallize *at a high temperature* with all proportions of $KAlSiO_4$. In 1931 Bannister and Hey[3] made it clear that at low temperatures no more than about 30 per cent of $KAlSiO_4$ is stable in $NaAlSiO_4$. In 1933 the writer suggested[4] that (in harmony with atom for atom explanation of crystal solution) $CaAl_2Si_2O_8$ does not intercrystallize with $NaAlSiO_4$, but that its components, $CaAlAlO_4$ and $SiSiO_4$, do so. Bowen himself reported in 1912 that $NaAlSiO_4$ can take into crystal solution at least as much as 5 per cent of $SiSiO_4$; so far as known to the writer no tests of the solubility of $CaAlAlO_4$ in $NaAlSiO_4$ have been made. It seems probable that if it is soluble it would increase the density and refractive index. Is it because $SiSiO_4$ would leave a vacancy in the structure and therefore lower the density and index that the combination of these two does not change the index (for the ordinary ray)?

In an attempt to solve the problem of the constitution of nepheline, the writer has made a rather detailed study of recent analyses of the mineral, with special reference to those which are accompanied by determinations of the physical properties. The results seem to be significant. The analyses in question have been calculated into $NaAlSiO_4$, $KAlSiO_4$ and other formulas which imply atom for atom replacement, that is, $CaAlAlO_4$, $SiSiO_4$, $AlSiO_3(OH)$ and $CaCaSiO_4$. The last one of these is the least satisfactory; perhaps impurities or inaccuracies of analysis are sufficient to render it unnecessary. The results are assembled in the following table.

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[1] Bowen, N. L., *Am. Jour. Sci.*, **33,** 49 and 551 (1912).

[2] Bowen, N. L., *Am. Jour. Sci.*, **43,** 115 (1917).

[3] *Min. Mag.*, **22,** 569 (1931).

[4] Optical Mineralogy, Part 2, 299 (1933).

Table 1. Composition of Nephelines in Molecular Per cent of $NaAlSiO_4$, $KAlSiO_4$ $CaAlAlO_4$, $SiSiO_4$, $AlSiO_3(OH)$ and $CaCaSiO_4$ as Calculated from Recent Analyses

No.	$NaAlSiO_4$	$KAlSiO_4$	$CaAlAlO_4$	$SiSiO_4$	$AlSiO_3(OH)$	$CaCaSiO_4$
A	100.0 (artificial)					
1	75.0	9.6	5.6	9.3		0.4
2	69.5	12.0	4.8	9.2	4.5	
3	64.2	14.5	4.8	9.1	7.4	
4	53.2	14.8	11.2	14.5	6.2	
5	74.5	15.6	2.3	7.1		0.4
6	69.0	16.2	5.5	7.3	2.0	
7	68.3	17.4	3.8	10.4		
8	55.1	23.0	1.8	17.9		2.2
9	64.2	26.5	5.5	1.9		2.0
10	81.2	14.6		2.4		1.8
11	60.2	35.2	1.0	2.4		1.2
12	73.0	11.8	1.4	13.0		0.7
13	68.1	20.2	1.2	3.3	7.2	
14	77.6	13.1	1.9	7.1		0.3
15	79.1	16.7		2.7		1.4
16	61.9	32.2	1.7	1.7		2.6
17	68.0	17.7	5.5	8.7		
18	77.8	10.9	2.2	9.0		
19	68.0	17.3	2.0	2.5	10.2	
20	75.9	14.3	1.7	8.1		

References for Table 1 and Figs. 1, 2, 3.

A. Bowen, N. L.: *Am. Jour. Sci.*, **33,** 49 (1912). A in Fig. 2 derived from Fig. 1.
1–9. Bannister, F. A., and Hey, M. H.: *Min. Mag.*, **22,** 569 (1931).
10. Dunham, K. C.: *Am. Mineral.*, **18,** 369 (1933).
11, 12. Bowen, N. L., and Ellestad, R. B.: *Am. Mineral.*, **21,** 363 (1936).
13. Walker, T. L., and Parsons, A. L.: *Univ. Toronto Geol. Stud.*, **21,** 8 (1925).
14–15. Zambonini, F.: *App. Mineral. Vesuvius and Rend. Accad. Fis. Mat. Napoli*, **15,** 26 (1912). Abst. in *Zeits. Krist.*, **55,** 301 (1915).
16. Zambonini, F.: *Rend. Accad. Fis. Mat. Napoli*, **49,** 83 (1910). Abst. in *Zeits. Krist.*, **52,** 313 (1913).
17. Starraba, F. S.: *Riv. Min. Crist. Ital.*, **48,** 53 (1917); *Min. Abst.* **I,** 108.
18. Washington, H. S., and Merwin, H. E.: *Jour. Wash. Acad. Sci.*, **5,** 389 (1915).
19. Walker, T. L., and Parsons, A. L.: *Univ. Toronto Geol. Stud.*, **22,** 5 (1926).
20. Barth, T.: *Vid. Akad. Oslo*, No. 8, 66 (1927).

If the components of nepheline were $NaAlSiO_4$, $KAlSiO_4$ and $CaAl_2Si_2O_8$, then the percentages of $CaAlAlO_4$ and $SiSiO_4$ would be equal in each analysis. Such a condition is found in only one analysis (16); in one case (9) $CaAlAlO_4$ is nearly three times as abundant as $SiSiO_4$, but in most cases $SiSiO_4$ is two to six times as plentiful as $CaAlAlO_4$. Of course this may be due to imperfections in the analyses, but such large discrepancies are somewhat surprising.

If nepheline contains all of these components (or even the first four), it is clear that there can be no simple relation between the tenor of $KAlSiO_4$ and the physical properties, since the latter must depend upon all of the components. To obtain an approximation of the properties in the $NaAlSiO_4$–$KAlSiO_4$ series those analyses with the least amounts of other components are used. In Fig. 1 all those analyses which contain at least 90 per cent of $NaAlSiO_4+KAlSiO_4$ are recorded. The results are reasonably concordant except for the specific gravity of No. 16. Since the refractive index of 16 falls on the line, it seems probable that the specific gravity is somewhat in error.

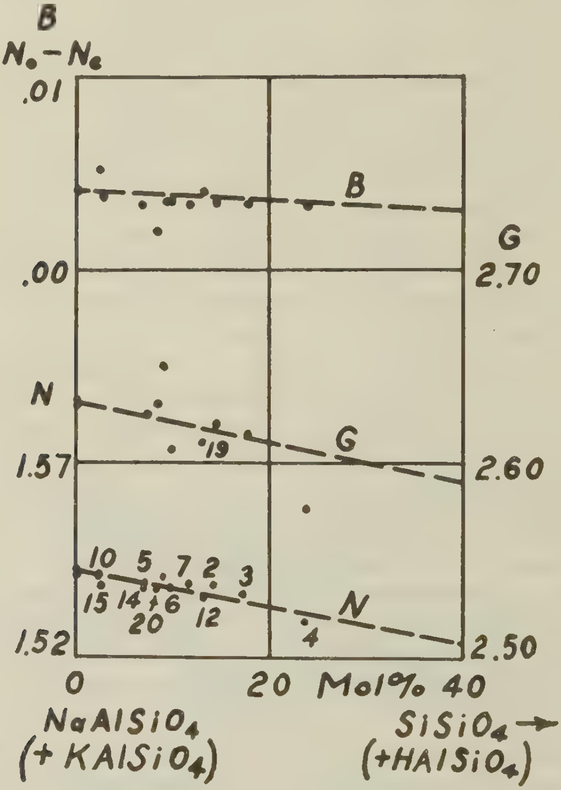


Fig. 1

Is it possible to find any correlation between the content of $SiSiO_4$ $(+HAlSiO_4)$ and the physical characters? If all the analyses containing about 15 per cent of $KAlSiO_4$ (exactly 11.8–17.7) are plotted on the basis of their tenor of $SiSiO_4$, as in Fig. 2, it is clear that the refractive index and specific gravity decrease with increase of this component. This condition is in harmony with the idea that the presence of $SiSiO_4$ implies a vacant position (occupied by the alkali atom in the usual structure). The fact that the decrease is not as rapid as required by assuming such vacant positions is perhaps due to the presence of water in them. Nearly all of these analyses show that water is present in small amount.

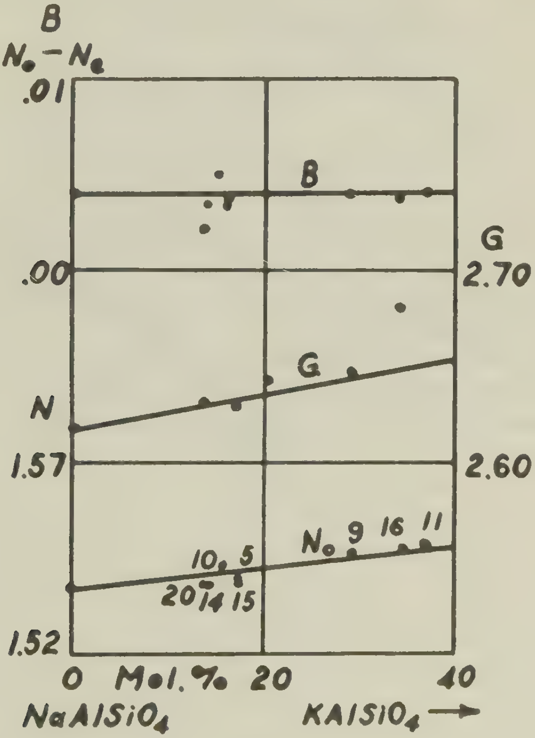
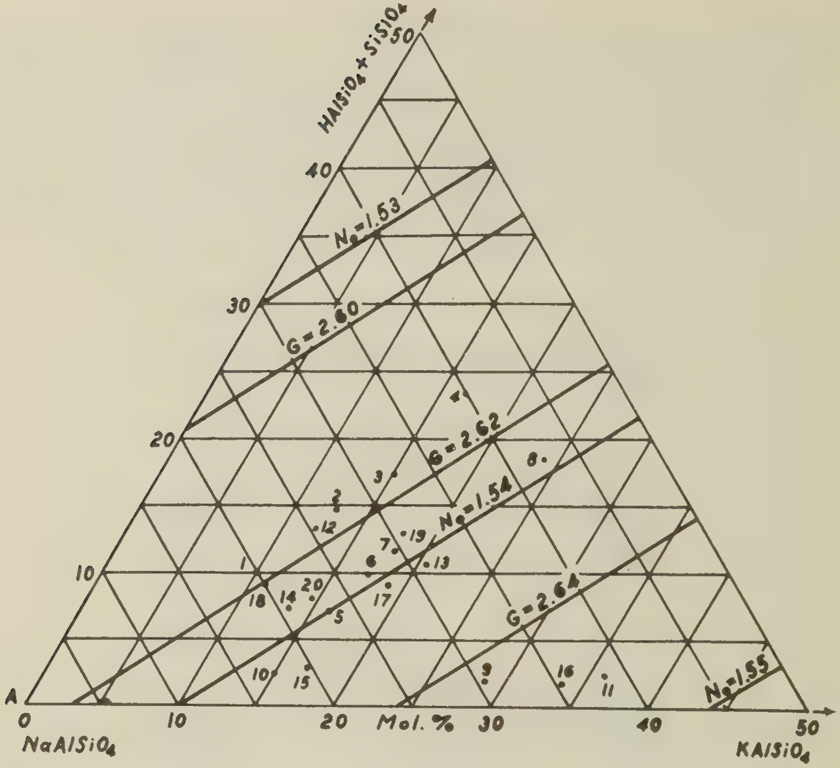


FIG. 2

Finally, in Fig. 3, an attempt is made to show the effects of both of these variables in one diagram. But the data are insufficient to give more than a first approximation, and such a diagram can never be more than an approximation because other variables (notably Ca) are disregarded. Figure 3 shows clearly that SiO_2 and K_2O vary quite independently of each other.


HAlSiO₄ + SiSiO₄
50
40
30
20
10
A
0
10
20
Mol. %
30
40
50
NaAlSiO₄
KAlSiO₄
Nₒ=1.53
G=2.60
G=2.62
Nₒ=1.54
G=2.64
Nₒ=1.55
4
3
8
2
12
19
7
6
13
1
20
18
14
5
17
10
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9
16
11

Fig. 3

THE VALIDITY OF PARAGONITE AS A MINERAL SPECIES

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Abstract

The occurrence of paragonite at three localities has been verified by new analyses.

The validity of paragonite, as a separate species, distinct from muscovite, has been questioned by McCormick[1] who, on the basis of a partial analysis, showing 1.77 per cent Na_2O and 4.6 per cent K_2O, concludes "that the so-called paragonite schist of Pizzo Forno, Switzerland, is primarily a muscovite schist containing about 37 per cent of the paragonite molecule. Paragonite as a distinct mineral has not been found in nature, indicating that it probably is an unstable molecule of the mica group."

This conclusion apparently was verified by analyses of various micas which had been made in the Geological Survey, U. S. Department of the Interior, in which only minor substitutions of potassium by sodium are shown. Thus, in the series of 17 analyses of lepidolite made by Stevens,[2] the highest percentage of Na_2O is 1.27 (sample no. 2). All the other 16 analyses show less than 1 per cent of Na_2O. In a series of alkali determinations in various micas made by Stevens and as yet unpublished similar results were obtained. The highest content of Na_2O in 12 muscovites is 1.81 per cent; 10 samples contain less than 1 per cent. In 6 biotites, and in taeniolite, phlogopite, zinnwaldite, and vermiculite, the content of Na_2O is less than 1 per cent. Many of these samples were selected from specimens containing albite, where a sodium environment suggested that paragonite might be present. For example, in an intergrowth of albite (with 11.58 per cent Na_2O, 0.30 per cent K_2O, and 0.08 per cent CaO) from the Pala View mine, on the southern slope of Stewart Hill, Pala, San Diego County, California, the intergrown mica nevertheless was found to contain only 1.06 per cent Na_2O with 9.97 per cent K_2O (a content of soda comparable with that of nearly all muscovites).

Similarly, only minor quantities of soda are reported in a series of analyses of muscovites by other workers. For example, in the list of 25 analyses of muscovite given by Volk,[3] the highest percentage of Na_2O is 1.70 (sample no. 8). Out of a series of 10 analyses of muscovite given by

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[1] McCormick, R. B., Paragonite from Pizzo Forno, Picino, Switzerland· *Am. Mineral.*, **19,** 431–432 (1934).

[2] Stevens, Rollin E., New analyses of lepidolites and their interpretation: *Am. Mineral.*, **23,** 615 (1938).

[3] Volk, G. W., Optical and chemical studies of muscovite: *Am. Mineral.*, **24,** 259 (1939).

Jakob,[4] one contains 3.77 per cent Na_2O (with 8.10 per cent of K_2O) whereas each of the others contains less than 2 per cent of Na_2O. In eleven additional analyses by Jakob,[5] the highest percentage of Na_2O is 2.21. From a third set[6] of eight analyses by Jakob the highest percentage of Na_2O is 2.08, and from a fourth set,[7] the highest percentage of Na_2O is 2.10 per cent.

Some of the recorded analyses of high-soda micas apparently are based on faulty analytical determinations. For example, the content of Na_2O in polylithionite from Kangerdluarsuk, Greenland, as given by Lorenzen,[8] namely 7.63 per cent Na_2O with 5.37 per cent K_2O, is much too high. On similar material Stevens[9] obtained 0.53 per cent Na_2O and 11.05 per cent K_2O. On polylithionite containing about 4 per cent of iron oxide from Narsarsuk, Greenland, Flink[10] likewise found but little soda, namely 1.61 per cent Na_2O with 11.05 per cent K_2O. The results obtained by Flink and Stevens confirm the conclusion that the percentage of Na_2O in polylithionite is not unusually high, as given by Lorenzen. The large quantity of lithia present in this mica probably accounts for the errors in the alkalies in Lorenzen's analysis.

The mica hallerite,[11] whose original analysis made on calcined material (the mineral contained 4.60 per cent "loss on ignition," fluorine absent) showed 1.26 per cent Li_2O, 7.63 per cent Na_2O and 3.12 per cent K_2O, was reanalyzed by Mallet[12] who obtained quite different results. Mallet's results on type material are: 0.36 per cent Li_2O, 3.04 per cent Na_2O, and 8.86 per cent K_2O. Hallerite, therefore, according to Mallet's results, is essentially muscovite with a relatively high content of sodium, equivalent to about 33 per cent of the paragonite molecule.

The recently described sericite[13] from Missouri "of unusual composition," with dominant soda, given as 5.27 per cent Na_2O with only 2.70 per cent K_2O, seemed to indicate a paragonite type of mica but these results could not be verified by us, as a redetermination of the alkalies (by Stevens) on a part of the original sample furnished by the late Prof. W. A. Tarr,[14] gave very different results, namely 1.82 per cent Na_2O and 7.60 per cent K_2O.

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[4] Jakob, Johann, Beiträge zur chemischen Konstitution der Glimmer. II. Mitteilung: Die Muskovite der Pegmatite. I. Teil: *Zeits. Krist.*, **62**, 445 (1925).

[5] Jakob, Johann, Beiträge zur chemischer Konstitution der Glimmer. V. Mitteilung: Die Muskovite der Pegmatite. II. Teil: *Zeits. Krist.*, **69**, 404 (1929).

[6] Jakob, Johann, Beiträge zur chemischen Konstitution der Glimmer. VI. Mitteilung: Die nicht pegmatitischen Muskovite. I. Teil: *Zeits. Krist.*, **69**, 512 (1929).

[7] Jakob, Johann, Beiträge zur chemischen Konstitution der Glimmer. VII. Mitteilung: Die Muskovite der Pegmatite. III. Teil: *Zeits. Krist.*, **70**, 494 (1929).

[8] Lorenzen, J., *Meddelelser om Grønland*, **2**, 70–73 (1881). Analysis quoted in Dana's *System of Mineralogy*, p. 627, anal. no. 7.

[9] Stevens, R. E., *op. cit.*, p. 615, anal. no. 17.

[10] Flink, G., *Meddelelser om Grønland*, **24**, 110–115 (1901).

[11] Barbier, Ph., Sur un nouveau mica du group paragonite· *Compt. Rendu*, **146**, 1220 (1908).

[12] Mallet, J., Sur l'identite de la hallerite et de la muscovite lithinifere· *Bull. Soc. franc. Mineral.*, **61**, 209–211 (1938).

[13] Meyer, D. B., A sericite of unusual composition: *Am. Mineral.*, **20**, 385 (1935).

Apparently, then, McCormick's conclusion would seem to be justified and paragonite possibly should be placed among the doubtful species.

However, two recent analyses of micas made in the Geological Survey show a high content of sodium and indicate that McCormick's conclusion may not be correct. The alkalies in mica from a schist (the Gassetts schist of Richardson) in Vermont, were determined by Dr. R. C. Wells of the Geological Survey who found 5.4 per cent Na_2O and 3.1 per cent K_2O, and in a new analysis (by Schaller) of euphyllite from Corundum Hill, Pa., soda was found to be greatly in excess of potash, though in the analyses of euphyllite listed on page 623 of Dana's *System of Mineralogy*, soda and potash are given in nearly equal quantities, with the percentages of potash slightly in excess. Also, a recent analysis of paragonite (locality not given) by Koch[15] shows 5.47 per cent Na_2O with only 0.46 per cent K_2O.

There are also in the literature a number of analyses of mica (paragonites), not yet shown to be faulty, in which soda greatly predominates over potash. In the older literature[16] about a dozen analyses of paragonite, with high content of soda, are given.

There seems, therfore, to be considerable evidence of the existence of a sodium mica. On the basis of this apparently conflicting evidence, it seemed desirable to reexamine the question of the existence of paragonite.

Accordingly, the alkalies were redetermined on three samples of mica from Europe labeled paragonite, and on euphyllite from Pennsylvania. The three samples from Europe were obtained from the U. S. National Museum through the courtesy of Dr. W. F. Foshag. One of these, however, although labeled "paragonite (var. pregrattite)," from Pregratten, Pustherthal, Tyrol (U. S. Nat. Mus. Coll. R 4415) is muscovite[17] with 0.07 per cent Li_2O, 1.81 per cent Na_2O, and 8.89 per cent K_2O, with no

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[14] In a personal communication to W. T. Schaller, Prof. Tarr wrote (April 9, 1937): "The crushed and powdered sample is material Mrs. Meyer used in her analyses."

[15] Koch, G., Chemische und physikalisch-optische Zusammenhänge innerhalb der Sprodglimmergruppe: *Chemie der Erde*, **9**, 463 (1935).

[16] As listed, for example, by Hintze, Carl, *Handbuch der Mineralogie*, **2**, pp. 648 and 649 (1897).

[17] The sample, of course, may not have been true pregrattite. Dana (*System*, p. 623, anal. no. 2) gives for pregrattite, 7.06 per cent Na_2O and 1.71 per cent K_2O.

Rb_2O and Cs_2O. The other two samples, Nos. 1 and 2 below, are paragonite.

No. 1 is labeled "paragonite (var. cossaite)," from Fenestrella, near Borgofranco, Valle-del Chisone, Piedmont, Italy (U. S. Nat. Mus. Coll. R 4416). It is very fine grained, compact, of typical sericitic pseudomorphic texture. Our analysis corresponds to analysis no. 5 as listed on p. 623 of Dana's *System of Mineralogy.*

No. 2 is labeled "paragonite," from Monte Campione, Switzerland (U. S. Nat. Mus. Coll. R 4414). The mica was separated from most of the associated quartz and kyanite with heavy solutions but the sample analyzed was estimated still to contain about 1 to 2 per cent of quartz and 2 to 3 per cent of kyanite. Our analysis corresponds to analysis no. 1 as listed on p. 623 of Dana's *System of Mineralogy.*

Both samples were carefully examined microscopically for the presence of any feldspar of which none could be seen.

No. 3 is euphyllite from Corundum Hill, Pa., obtained from the Brush type collection at Yale University by Dr. Michael Fleischer through the courtesy of Dean C. H. Warren. As far as can be ascertained this sample (Yale No. 3725) represents the type material analyzed by Smith and Brush, the results being published in 1853.[18] The specimen, a coarse aggregate of euphyllite and black tourmaline, was broken down by rolling on a steel plate, so as to crush finely the more brittle tourmaline and other associated minerals and leave much of the euphyllite in relatively large sheets. The material was then sieved, the large sheets of mica being retained. After further selection and purification, the mica was ground and analyzed.

The alkalies determined in these three samples of high soda micas are shown below.

ALKALIES IN PARAGONITES

[By R. E. Stevens]

	1[a] Fenestrella, Italy	2[b] Monte Campione, Switzerland	3[c] Pennsylvania	Calculated for paragonite
Na_2O	7.26	6.28	5.64	8.11
K_2O	1.01	2.17	1.71	—

[a] In addition, 0.13 per cent Li_2O, no rubidium or cesium.

[b] In addition, 0.08 per cent Li_2O, 0.12 per cent Rb_2O, no cesium.

[c] In addition, 0.73 per cent Li_2O, 0.11 per cent Rb_2O, no cesium.

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[18] A new and complete analysis will be given and discussed in a later paper.

Paragonite, therefore, is a valid species and the conclusion of McCormick that "Paragonite as a distinct mineral has not yet been found in nature . . . " is incorrect. Three localities may be given with assurance: Fenestrella, Italy; Monte Campione, Switzerland; and Corundum Hill, Pa. Doubtless other localities will be added when the older analyses are verified.

Plotting selected analyses of muscovite and paragonite on the basis of their weight percentage composition of the two end members (M)$H_2KAl_3Si_3O_{12}$ with 11.82 per cent K_2O and (P)$H_2NaAl_3Si_3O_{12}$ with 8.11 per cent Na_2O, there is an almost continuous series from 95M, 5P to about 60M, 40P and from 30M, 70P to nearly 100P. The large gap from 60M, 40P, to 30M, 70P apparently has no representative.

It seems to be impossible to differentiate between muscovite and paragonite on the basis of their optical properties, those of paragonite lying within the variable range of the indices of refraction of the muscovites, for most of which both β and γ lie between 1.590 and 1.615, with a concentration of the values for γ from 1.598 to 1.604. Thus Koch gives: $\alpha = 1.577$, $\beta = 1.599$, and $\gamma = 1.605$ for the paragonite analyzed by him. The paragonite from Fenestrella (no. 1) has $\beta = 1.599$ and $\gamma = 1.604$ and the paragonite from Monte Campione (no. 2) has $\beta = 1.600$ and $\gamma = 1.605$, with a few scales (possibly muscovite?) with both β and γ very slightly under 1.600. The euphyllite (no. 3) has about $\beta = 1.605$ and $\gamma = 1.609$, slightly variable.

CHILEAN HEXAHEDRITES AND THE COMPOSITION OF ALL HEXAHEDRITES

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ABSTRACT

Many hexahedrites have been reported from Chile and since they are found over a rather limited geographical area, are most likely not all separate falls. Chemical investigations were made in the hope that some significant differences in composition would be found in them, but all have proven to be very similar. Chilean hexahedrites when compared with others from all parts of the world, are likewise found to be chemically similar. The composition of hexahedrites is now well established. Their position in the equilibrium diagram of the iron-nickel system is discussed. Kamacite in octahedrites is shown to be similar to hexahedrites.

According to the records of the U. S. National Museum, ten hexahedrite irons are known from Chile, most of them having been discovered within a rather limited geographical area. Hexahedrites are an uncommon type of iron meteorite and the finding of ten separate falls of this class in such a restricted area is more than can be considered logical.

In the following table the names of all hexahedrites, together with the latitudes and longitudes of those which can definitely be located, are given. As meteorites are named after the town or other well known geographical feature near the point of their discovery, the latitude and longitude denotes the geographical spot for which the meteorite was named. Since the area in Chile is very sparsely populated, with few towns, the localities given usually represent the town to which the meteorite was carried, and the distribution of the meteoritic material may be more limited than the table indicates. The extreme differences in latitude between them is 8°54′, while the maximum difference in longitude is 1°56′.

It is evident from Table 1 that these meteorites are, with the exception of San Martin, rather closely grouped geographically, and most likely represent a shower of iron falls.

All of these hexahedrites are homogeneous in structure and large polished and etched faces show a continuous, unbroken structure throughout. A few small inclusions of troilite are present and around an occasional troilite mass there are some thin zones of schreibersite. At times a rectangular area of schreibersite is included within the troilite. Delicate needles of rhabdite are present and rather evenly distributed but are not particularly numerous. The areas selected for analyses were free from

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[1] Published with the permission of the Secretary of the Smithsonian Institution.

TABLE 1. CHILEAN HEXAHEDRITES

Name	Latitude	Longitude	Known weights
Cerros del Buei Muerto	22°40′ S	69°50′ W	75 kilograms
Coya Norte[1]	22°20′ S	69°40′ W	17.9 kilograms
Mejillones	23° 7′ S	70°30′ W	1185 grams[2]
Negrillos[1]	On the Iquique Pampa		28.5 kilograms
Puripica[1]	Province of Antofagasta		19 kilograms
Rio Loa[1]	21°26′ S	70° 5′ W	4 kilograms
San Martin[3]	30° 0′ S	71°18′ W	
Sierra Gorda[1]	22°53′ S	69°18′ W	22 kilograms
Union	23° 3′ S	69°30′ W	22 kilograms
Filomena[1]	23° 0′ S	69°26′ W	21.1 kilograms

[1] Described for first time.

[2] Weight reported in collections. Original find must have been much greater, but location of main mass is now unknown.

[3] Main mass in Kiel, Germany. Weight is not listed.

any conspicuous inclusions, save the needles of rhabdite. Therefore, these analyses express as nearly as possible the composition of the main mass.

Table 2 contains the analyses of the newly reported meteorites and indicates how strikingly similar they are. It is impossible to find any distinguishing differences between any of these meteorites.

After determining the definite proportion between iron and nickel in the Chilean material, it was then desirable to compare these results with those published for other hexahedrites. Farrington[2] compiled a list of

TABLE 2. NEW CHILEAN HEXAHEDRITES

Name	Fe	Ni	Co	P	S	Cr	Ins.	Total
Coya Norte	93.74	5.51	.37	.30	trace	.03	.03	99.95
Negrillos	93.94	5.32	.35	.22	trace	.02	.02	99.87
Puripica	93.83	5.77	.26	.19	trace	trace	.03	100.08
Rio Loa	93.33	5.70	N.D.	.28	trace	trace	.01	99.32
Sierra Gorda	93.44	5.58	.25	.23	trace	trace	.01	99.51
Union[1]	93.09	5.63	N.D.	N.D.				
Filomena	N.D.	5.73	.21	.30	trace		.01	

Average Fe content 93.56
Average Ni content 5.60

[1] *Bull. Suiesse. de Min. et Petr.*, **17** (1937). Ni was originally reported as 4.66%. Private communication from J. Buffle reports the redetermination of Ni to be 5.63%.

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[2] Farrington, O. C., *Field Museum Publication 120,* **3,** No. 5 (1907).

analyses of hexahedrites which showed some variation in the percentages of iron and nickel. In the 38 analyses given by Farrington, the percentages of iron varies from a low of 91.86% to a high of 97.90%, and likewise the range of nickel lies between 2.10% and 7.42%. It is interesting to note that the higher value for the iron is in the same analysis as the low nickel determination. It has been found that the determination of nickel in the presence of much iron leads to analytical difficulties and low nickel percentages in so many old analyses are incorrect.[3]

TABLE 3. ANALYSES OF HEXAHEDRITE METEORITES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Fe	93.36	94.14	93.75	93.30	93.93	94.02	93.39	94.03	93.39	93.47	93.59	93.62	93.06	93.75	93.59	94.05
Ni	5.78	5.30	5.51	5.79	5.52	5.48	5.62	5.33	5.69	5.55	5.68	5.21	5.35	5.43	5.59	5.48
Co	.75	.63	.51	.29	.61	.22	.58	.95	.78	.52	.66	.92	1.00	.58	.78	
S		.19		.18		.04		.07	trace	none	.08	.08	.08	.08	trace	
P	.25	.28	.20	.20	.34	.30	.31	.23	.22	.27	.25	.24	.31	.19	.32	
C	.03		.06		.04				.12	.03		.09				
Cr		.05		.04		.02		.02			.02	.05	.23			
Cu		.06		trace	.02			.04	trace	trace	.04	.07				
Ins.				.08				.01					.08		.07	
Cl					.06											

Average Fe content 93.652
Average Ni content 5.519

Col. 1—Uwet, Africa	*Min. Mag.*, **17**, 127 (1914).
2—Walker Co., Alabama	*Meteoritenkunde*, **3**, 173 (1897).
3—Iredell, Texas	*Am. Jour. Sci.*, **8**, 415 (1899).
4—Bruno, Sask., Canada	*Am. Jour. Sci.*, **31**, 209 (1936).
5—Murphy, North Carolina	*Meteoritenkunde*, **3**, 227 (1905).
6—Cedartown, Georgia	To be described by S. H. Perry.
7—Summit, Alabama	*Am. Jour. Sci.*, **40**, 322 (1890).
8—Scottsville, Kentucky	*Meteoritenkunde*, **3**, 218 (1905).
9—Warialda, Australia	*Rec. Geol. Surv., N. S. W.*, **10**, 75 (1921).
10—Barraba, Australia	*Rec. Geol. Surv., N. S. W.*, **10**, 75 (1921).
11—Hex River, Africa	*Meteoritenkunde*, **3**, 225 (1905).
12—Braunau, Bohemia	*Meteoritenkunde*, **3**, 207 (1905).
13—Holland's Store, Georgia	*Meteoritenkunde*, **3**, 240 (1905).
14—Cerros del Buei Muerto, Chile	*Chemie der Erde*, **7**, (3) 499, (1932).
15—Coahuila, Mexico[1]	New analysis, unpublished (E. P. H.)
16—Boguslavkia, Siberia, USSR	New analysis, unpublished (E. P. H.)

[1] Of the 3 best analyses for this meteorite, the nickel content was reported as 5.62; 6.62; 7.42. Reanalysis by E. P. Henderson was made to establish the correct value.

Sixteen different analyses are listed in Table 3 which agree with the findings given above for the Chilean hexahedrites. Such consistent agreement between all of these results must have some fundamental significance. The average value for iron in the Chilean meteorites here reported for the first time is 93.56% and for the other 16 hexahedrites here referred to is 93.65%. The percentage of nickel is 5.60% in the Chilean material against 5.519% in the other table.

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[3] Henderson, E. P., Methods of determining nickel and cobalt in meteoric iron: *Am. Jour. Sci.*, **239**, 372 (1941).

Hexahedrites are similar in structure to kamacite, the principal alloy in octahedrites. Table 4 offers a comparison between some analyses of kamacite and the average analysis for hexahedrites.

The agreement is very close between these kamacite and hexahedrite analyses. Perhaps the reason for the kamacite from octahedrites averaging more nickel than the hexahedrites is that it is very difficult to remove a sample of kamacite from an octahedrite and be certain that no taenite is included.

Table 4. Kamacite Analyses

	Bendigo	Welland	Glorietta	Canyon Diablo	Magura	Magura	Magura	Staunton	Toluca	Canyon Diablo	Santa[1] Luzia	Average for kamacite and hexahedrite	
												Kamacite	Hexahedrite
Fe	93.01	93.09	92.62	92.62	93.01	92.94	93.27	93.89	94.05	94.09	93.88	93.35	93.65
Ni	6.22	6.69	6.55	6.81	6.25	6.18	6.04	5.30	5.26	5.51	6.14	6.07	5.52
Co	.77	.25	.83	.57	.74	.88	.64	.61	.57	—	.096	.56	.59

[1] V. B. Meen, Santa Luzia de Goyaz meteorite; *Am. Mineral.*, **24**, 600 (1939).
All other kamacite analyses taken from O. C. Farrington, *Meteorites*, privately published (1915).

The compositions of hexahedrites agree with data of the equilibrium diagram of Owen and Sulley for the iron-nickel system.[4]

In this diagram the α-$\alpha\gamma$ boundary shows a maximum solubility of 5.6% Ni in Fe at about 400° C. The solubility decreases as the temperature is lowered. If the α-$\alpha\gamma$ boundary line in this diagram is extended down to 200° C., the nickel content would be 5.3 %.This lowering of the solubility of Ni between the temperatures of 400° C. and 200° C. may not decrease quite as rapidly as they indicate and the boundary should be more nearly straight. In Table 2 the average Ni for the hexahedrites is 5.60% while in Table 3 it is 5.519%.

Hexahedrites therefore fall near the α-$\alpha\gamma$ boundary and being composed essentially of one compound, kamacite or α-iron, should contain about 5.5% Ni. Kamacite from octahedrites has been analyzed and its Ni content should lie on the α-$\alpha\gamma$ boundary and none should fall into the α-iron field. Coarsest octahedrites, consisting essentially of kamacite (α-iron) with a very little taenite (γ-iron) should lie immediately within the $\alpha\gamma$ field.

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[4] Owen, E. A., and Sulley, A. H., Equilibrium diagram of iron-nickel alloys· *Phil. Mag. and Jour. Sci.*, **27**, No. 184, 633, May (1939).

Of the kamacite analysis in Table 4, two have nickel values (5.30% and 5.26% respectively) that are below the average of hexahedrites or α-iron; three have nickel values (6.69%, 6.55% and 6.81% respectively) which are higher than would be expected for a true homogeneous kamacite and these may be contaminated with taenite inclusions.

The list is only of qualitative value and is repeated here to show how the average kamacite compositions compares with the hexahedrite, as well as agrees with the equilibrium diagram for iron and nickel. The average for kamacite is 6.07% Ni which is located on the diagram, as it should be, just within the $\alpha+\gamma$ field. The composition for hexahedrites is given with some degree of confidence. The discussion of the composition of kamacite from octahedrites is introduced to show relationship. The marginal boundary between hexahedrites and octahedrites (coarse octahedrites) is perhaps somewhere between these values. Analyses of the coarsest octahedrites are being made in the hope of further defining the boundary between hexahedrites (α-iron) and octahedrites ($\alpha+\gamma$-iron).

Conclusions

1. Chilean hexahedrites have identical compositions and are recovered from a long, narrow strip of country in northern Chile. Very likely most, but perhaps not all, of these are related to a single shower. It is suggested that the named meteorites in this paper be referred to as North Chilean hexahedrites, while all other names now in the literature be regarded as synonyms.

(2) The composition of all hexahedrites is very definite. The nickel content lies between 5.5% and 5.6%.

(3) Relationship between hexahedrites and octahedrites is discussed and the lower nickel range for octahedrites seems somewhat definitely established somewhere between 5.52% and 6%. The coarsest of the octahedrites should contain slightly higher than 5.60% nickel and taenite would be scarcely detectable in octahedrites of less than 6% nickel.

HYDROTHERMAL DEPOSITS IN THE SPECIMEN MOUNTAIN VOLCANICS, ROCKY MOUNTAIN NATIONAL PARK, COLORADO

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Abstract

Specimen Mountain, in Rocky Mountain National Park, Colorado, is a denuded Tertiary explosive volcano. Thrust faults displace its core and flanking pyroclastics and flows and have provided channelways for hydrothermal solutions rising from depth. Jasper and opal deposited from these solutions have replaced pitchstone flows adjacent to the faults. Locally the jasper forms geodes, partly or completely filled with agate, onyx, opal, calcite, and minor amounts of allophane and chloropal. Sufficient time elapsed between the periods of eruptive volcanism and hydrothermal mineralization to permit an intervening period of extensive thrust faulting.

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Location

Specimen Mountain (elevation 12,482 feet) is a prominent landmark standing above the continental divide at the crest of the Front Range of Colorado (Fig. 1). It lies just north of Poudre Lake at Milner Pass in the northwestern corner of Rocky Mountain National Park. Streams on the south side drain into the headwaters of the Cache la Poudre River; streams on the north side enter the headwaters of the Colorado River.

During the summer months Specimen Mountain is easily reached by excellent auto roads from either Estes Park or Grand Lake. Horse and foot trails lead from Poudre Lake into the heart of the area described in this paper.

Field Work and Acknowledgments

The writer visited Specimen Mountain on several occasions during the summers of 1934 to 1940, but it was not until the summer of 1940 that an extensive investigation was begun. In September, 1940, working as a collaborator with the National Park Service and aided by funds generously donated by the Research Council of the University of Colorado, a month was spent in the area.

The writer wishes to express his appreciation for the services of Mr. Olwin Woodbury, who spent two weeks in the area as field assistant. Mr. Raymond Gregg of the National Park Service greatly expedited the work by his interest and cooperation; Dr. Carol Wegemann, Mr. David Canfield and Mr. H. E. Rothrock, all of the National Park Service, facilitated the work by cooperating to the fullest extent. Dr. Wegemann, who spent a day in the field with the writer, offered many helpful suggestions. Dr. W. O. Thompson of the University of Colorado critically read the manuscript.

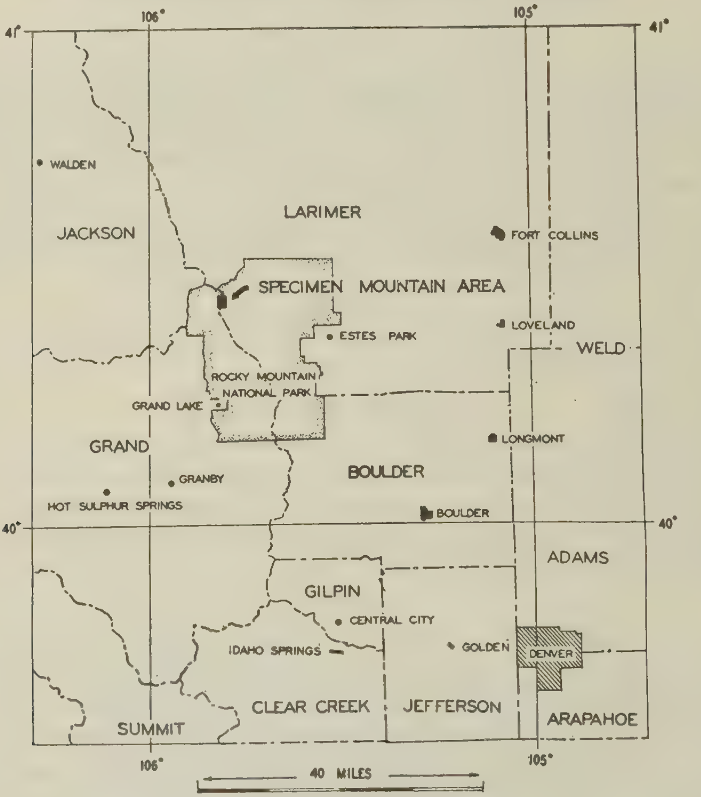

Fig. 1. Outline map of north-central Colorado showing location of Specimen Mountain area.

Geologic Setting

The oldest rocks of the area are the gneisses and schists of the pre-Cambrian Idaho Springs formation, which is composed of highly metamorphosed sediments, intensely folded and injected by sills of pegmatite, aplite and gneissoid granite. These rocks are displaced by extensive faults and shear zones of unknown age.

Specimen Mountain consists essentially of the dissected remnants of a Tertiary explosive volcano which mantled a broad area of maturely dissected pre-Cambrian rocks with a thick covering of pyroclastics and lava flows. Streams and glaciers have effectively exposed the core and flanking ejectamenta of what at one time must have been a very impressive volcanic cone (Fig. 2). Specimen Mountain itself is actually an outlier of an extensive volcanic area which lies to the west and northwest in the Never Summer Range.

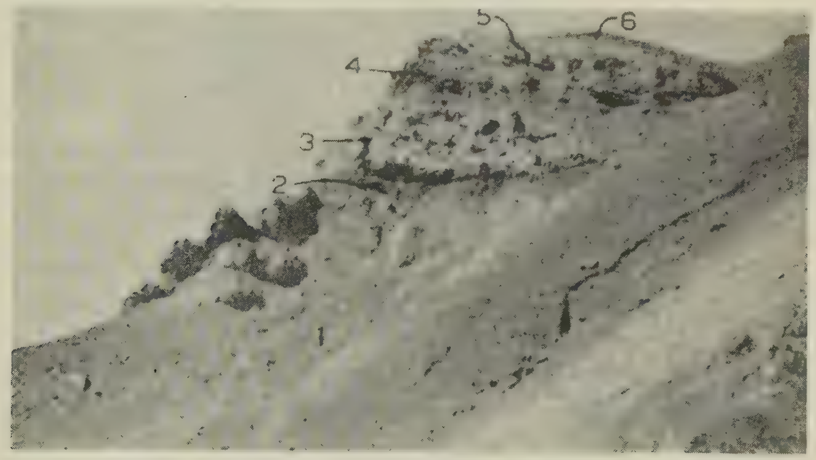

Fig. 2. Cliff exposure of pyroclastics and flows. Southwest side of Specimen Mountain.
1—Ash and breccia with agglomerate layers.
2—Pitchstone containing jasper lenses and geodes.
3—Ash and breccia.
4—Pitchstone containing jasper layers and geodes.
5—Jasper layer partly replacing pitchstone.
6—Ash bed.

The top of Specimen Mountain (Fig. 3) approximately marks the center of the conduit which provided a channelway for the movement of molten lava from depth. In plan the conduit is subcircular and is filled with a porphyritic rock near quartz trachyte in composition. This rock consists largely of phenocrysts of sanidine embedded in a dense to glassy groundmass containing, in addition to sanidine, biotite, amphibole, pyroxene, magnetite, and, locally, abundant tridymite.

The structural history of Specimen Mountain is complex. Field work has disclosed the fact that the cessation of volcanic activity was marked by a period of thrust faulting, which produced a series of thrust slices each bounded above and below by flatly dipping fault zones. These faults, which are exposed best in the bedded pyroclastics on the west side of Specimen Mountain, in general strike northwest and dip to the northeast at about thirty degrees. The faults provided channelways for the circulation of late mineralizing solutions from which was deposited an interesting assemblage of minerals.

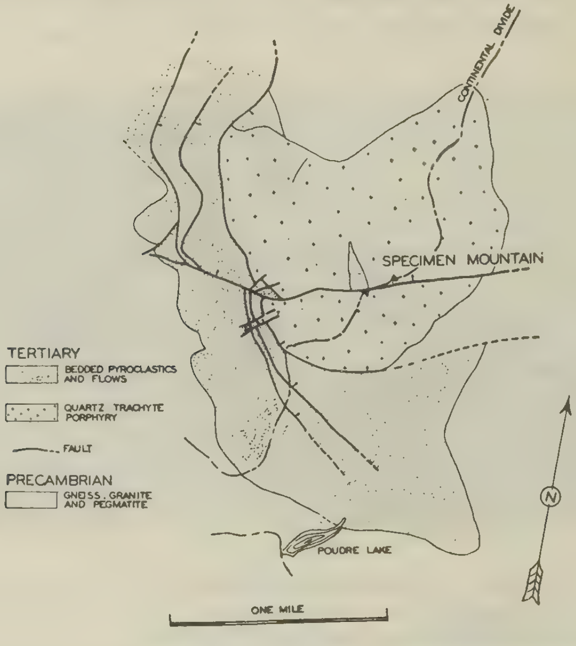

Fig. 3. Outline geologic map, Specimen Mountain area, Colorado. Geology plotted in field on aerial photographs.

Bedded pyroclastics and flows are not present in the east and north sides of Specimen Mountain, and those that are found on the west and south sides probably are present only by virtue of the fact that they occur in thrust fault blocks and were buried and protected from rapid denudation by a mass of rock greatly thickened by faulting.

The pyroclastics and glassy and porphyritic flows form a thick section ranging from basalt to quartz trachyte in composition. Thick beds of agglomerate, breccia, ash and cinders, and tuff are locally prominent. In general, the lowest and oldest beds or flows, at the bottom of the section, are more mafic than those higher up. The uppermost layers have essentially the same composition as the rock in the core of the volcano. Noteworthy are two layers of pitchstone, each with a thickness averaging about fifteen feet and occurring high in the section. These are quickly chilled lava flows and crop out in the cliffs on the west and southwest sides of Specimen Mountain.

MINERAL DEPOSITS

General Statement

The pitchstone layers have been replaced in part by abundant jasper and opal. These minerals are found in small quantity in other rock types, but their concentration in the pitchstone indicates that this rock provided the most favorable environment for deposition. Jasper and opal are abundant also in the faults cutting the pyroclastics. Associated with the jasper and opal are minor amounts of other minerals, including agate, onyx, calcite, allophane, and chloropal (nontronite).

Structural Control

The jasper and opal and accompanying minerals are structurally related to the thrust faults as is indicated in Fig. 4. Mineralizing solutions moving along these faults deposited part of their load in the faults and locally silicified the fault breccia. Silicification is present in most exposures of the faults, but is most prominent where the fault breccia is thickest.

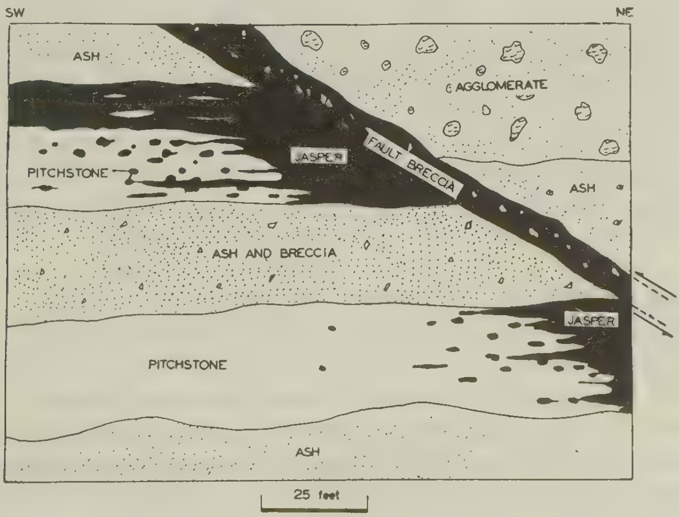

FIG. 4. Idealized cross section showing jasperization of pitchstone flows adjacent to a thrust fault. Southwest side of Specimen Mountain.

The extent to which the rocks adjacent to the faults are replaced probably reflects the permeability of the various layers. Tuff beds, agglomerates, and ash beds, because of the presence of impervious bentonitic alteration products, were unfavorable media for the free circulation of solutions. Likewise, massive, dense flow-rocks in the lower part of the section did not permit entrance of large amounts of solutions. However, the brittle pitchstone beds in the upper part of the section are highly fractured and relatively pervious.

Inspection of Figure 4 shows that the replacement of the pitchstone next to the faults resulted in complete obliteration of all previous structures, except bedding. As the solutions moved away from the faults, the replacing action became less intense and only part of the original rock was replaced. At a distance from the faults the only manifestations of replacement are jasper geodes, or concretions, which are localized by closely spaced, onion-like spherical shrinkage fractures.

Minor fractures in other rock types contain inconspicuous deposits of the minerals found in the pitchstone.

Mineralogy

The *jasper* in the faults and pitchstone flows consists largely of gray-brown to red-brown chalcedony containing disseminated fine-grained hematite and limonite. Contacts between the jasper and pitchstone are billowy. In detail the surfaces of the jasper masses display crowded knotty, approximately hemispherical protuberances ranging from a fraction of an inch to several inches in width. These appear to be layered but are actually massive within. The layered appearance results from the partial preservation of closely spaced flow structures in the replaced pitchstone.

Gray and green *agate*, *onyx*, *opal* and *calcite* partially or completely fill the interiors of hollow concretions, or geodes (Fig. 5). These minerals were deposited after the interiors were etched out because of a change in the character of the mineralizing solutions after deposition of the jasper. Floors of many of the cavities are covered with corroded angular jasper fragments cemented by the younger minerals.

The *agate* coats the walls and roofs of the cavities and on the floors grades into flat intercalated layers of opal and chalcedony in the form of *onyx*. The thickness of the agate layer rarely exceeds an eighth of an inch, but some onyx masses are several inches thick. Agate and onyx were deposited contemporaneously. The greater thickness and flat layering of the onyx indicate gravitative control.

Green *chalcedony* is colored by small amounts of a disseminated, dendritic, amorphous, yellow-green isotropic material, probably consisting of a mixture of opal, allophane, and chloropal (Fig. 9A). Chemical tests of this material gave widely divergent results, but water, silica, aluminum and iron were repeatedly detected in samples. Opal was determined by its index (1.42 to 1.44); optical and chemical tests suggest the presence of allophane and chloropal (hydrous aluminum and iron silicate).

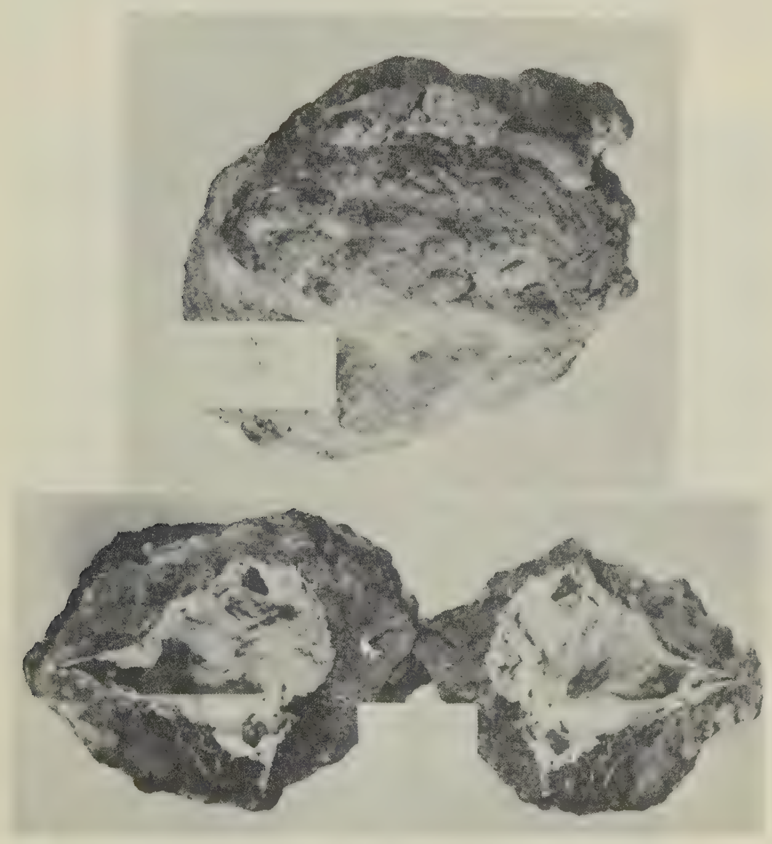

FIG. 5. Concretion partly filled with agate and onyx. Specimen Mountain. Upper view shows concretion as it appeared when found. Lower view shows the same concretion after it had been broken open. Onyx consists of alternating layers of opal (white) and chalcedony (gray).

The *opal* is generally opaque white or yellowish-white; in some specimens it is transparent and of inferior gem quality. It is commonly interlayered with the chalcedony, but in some specimens tiny anastomosing veinlets have entered the walls of the concretions. Some opal occurs in pulverulent white masses completely filling cavities in the jasper. Rarely, massive white opal completely fills the interior of a concretion.

Platy *calcite* in flat rhombohedrons is present in hemispherical aggregates, or isolated crystals in some of the concretions. It is an early mineral and was deposited simultaneously with early generations of opal and chalcedony. Much of the calcite has been leached out of lamellar intergrowths with opal and chalcedony and has left porous platy aggregates of these minerals (Fig. 8). Later generations of opal and chalcedony locally have coated or replaced the calcite and form delicately banded pseudomorphs (Figs. 6 and 7).

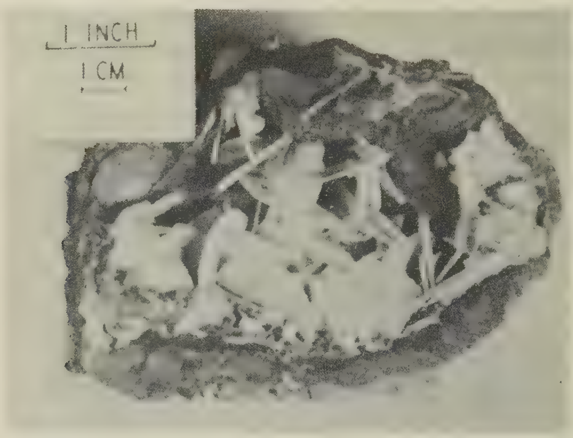

Fig. 6. Concretion containing chalcedony and opal pseudomorphs after calcite. Inner walls of concretion are coated with layered chalcedony and opal. Specimen Mountain.

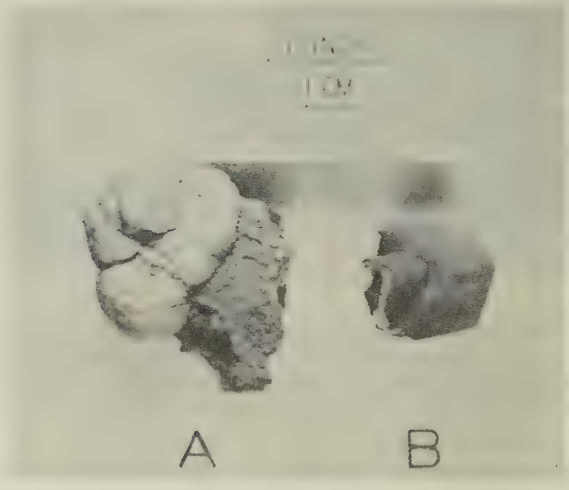

Fig. 7.

A. Chalcedony pseudomorphous after platy calcite aggregate.

B. Chalcedony and opal replacing and coating single tabular crystal of calcite.

Under the microscope it is seen that the calcite was deposited in at least two generations. The chalcedony and opal are birefringent (Fig. 9) and exhibit banded or feathery colloform structures. Angular and subgraphic intergrowths of platy calcite and chalcedony are abundant. Pseudomorphs of chalcedony and opal attest to the original presence of much calcite. Most of the replaced calcite was early and adhered to the walls of the cavities.

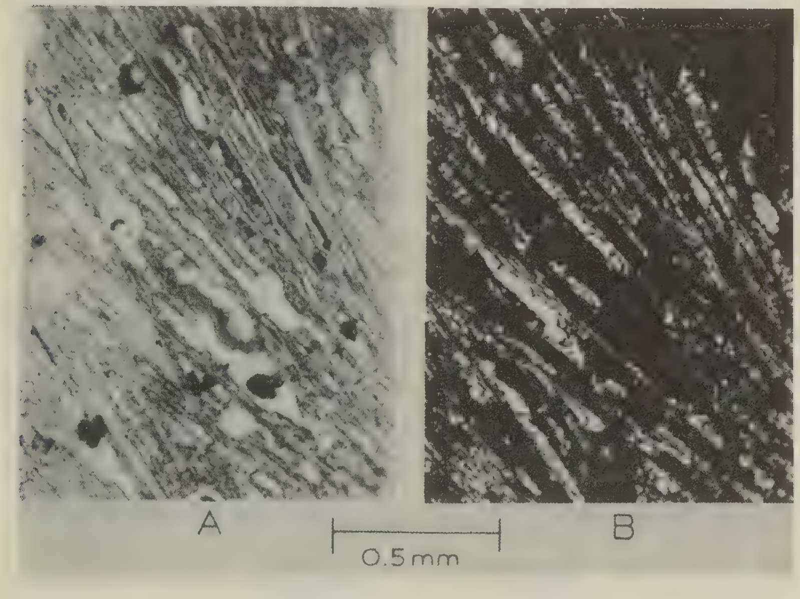

FIG. 8. Photomicrographs of thin sections of platy opal in porous aggregate from which interlaminated calcite has been dissolved. A second generation of opal coats the walls of the cavities originally occupied by calcite.

A. Plain light. White patches are cavities.

B. Crossed nicols. Note birefringent character of opal.

Paragenesis

Jasper replacement of pitchstone layers marked the inception of hydrothermal mineralization. Change in the character of the solutions caused dissolution of the interiors of many isolated concretions of jasper, and was followed by deposition of calcite, chalcedony, and opal in the interiors of the concretions. Calcite was an early mineral and was deposited in at least two generations. Chalcedony and opal, forming simultaneously with the calcite, in part replaced it. Pulsating deposition of the silica minerals, as shown by the banding, continued after the cessation of calcite precipitation. Late chalcedony, colored green by an amorphous mixture of opal, allophane, and chloropal, closed the period of mineralization.

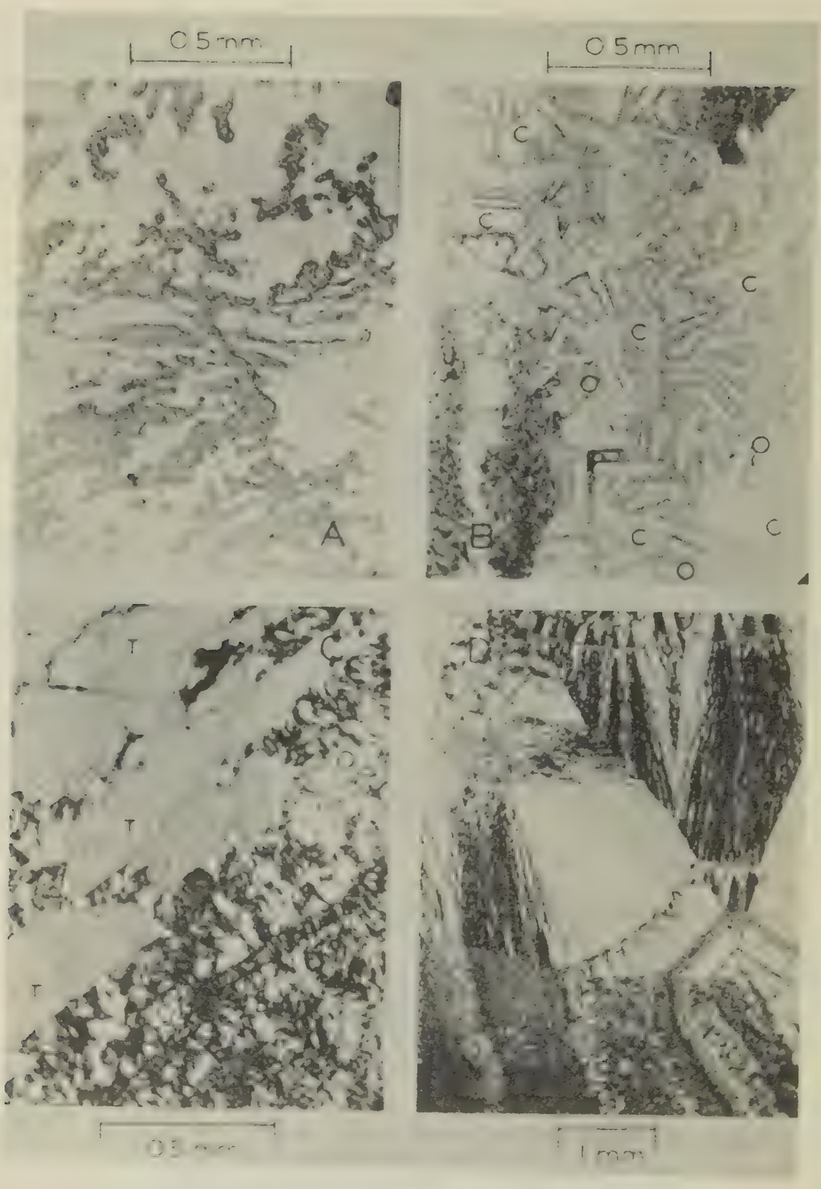

FIG. 9. Photomicrographs of thin sections of minerals in concretions.
A. Dendritic masses of chloropal and allophane in chalcedony (colorless). Plain light.
B. Chalcedonized intergrowth of opal (O) and platy calcite. Chalcedony (C) has completely replaced original calcite which rested on jasper walls of concretion. Plain light.
C. Intergrowth of platy calcite (T) and colloform birefringent opal (O). Crossed nicols.
D. Layered, birefringent chalcedony showing feathery colloform structures. Crossed nicols.

Solution of calcite from intergrowths with opal and chalcedony may have been caused by surface water but deposition of additional silica on the walls of casts of the calcite suggests that removal of calcite was caused by hypogene solutions.

Origin and Character of Mineralizing Solutions

Thrust fault zones cutting the volcanics are highly brecciated, exposing the area to localized warm or hot mineral-bearing solutions rising from depth. Mineral deposition came late in the igneous history of Specimen Mountain for the faulting occurred only after the volcano had become extinct. The rocks in the conduit were at least cool enough to serve as rigid bodies to the forces causing the faulting. Sufficient time elapsed between the periods of ejection of lava and pyroclastics and the formation of mineral deposits to permit a prolonged period of thrust-faulting.

The mineral-bearing solutions were probably warm waters deriving their heat from hot rocks near the source of the volcanics. The transported mineral load may have been in part a contribution from the rocks at the source of the waters, and in part material dissolved from the wall rocks of the channelways. As the solutions issued at the surface they probably had all the characteristics of the hot springs abundant in many regions of expiring volcanic activity.

Early precipitation of calcite suggests nearly neutral or alkaline waters, but partial resolution of calcite suggests a change to a more acid nature toward the end of the period of mineralization. In any event, the mineral solutions were probably pulsating in character, both as regards chemical composition and rate of flow.

NOTES AND NEWS

THE FORMATION OF JAROSITE ON PYRITE ORNAMENTS

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The American Museum of Natural History, New York, N. Y.

In the course of archaeological investigations in Sinaloa, Mexico, Mr. Gordon Eckholm of the Department of Anthropology of The American Museum of Natural History, excavated a number of Indian skeletons which can be dated at approximately 1350 A.D. They were buried in an artificial, small dirt mound rising above the flood plain of the Sinaloa River, four miles south of Guasave, Sinaloa, Mexico. After the removal of the bones of one skeleton, which were in very poor condition, remnants of a necklace were found which, from its position, must have lain around the neck of the body.

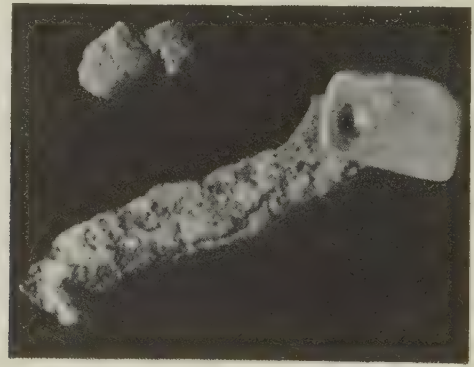

Fig. 1

The necklace (A.M.N.H., Dept. of Anthrop. #30. 2-5110) originally consisted of small cylindrical pyrite beads, with several turquoise pendants strung between them. Like the bones, the necklace has suffered from its burial and was collected in fragments. From a mineralogical standpoint, its present condition is most interesting.

The cylindrical pyrite beads seem to have been originally about 5 mm. in diameter and 2.5 to 4 mm. in length. The three turquoise pendants are approximately 15 by 10 by 2.5 mm. in size. The turquoise is crudely polished and each has a small hole drilled at one end. They obviously were strung between the pyrite beads and extended below them, much as in more modern, all turquoise, Indian necklaces to be seen today. The pyrite beads were, no doubt, equally well rounded, drilled and finished, but they have not survived in the fresh, unaltered condition of the turquoise. The polishing and shaping of the turquoise is on a par with that obtained today by primitive methods. It does not seem to have suffered or been changed in any way by its burial. Its color is slightly muddy, though here and there small fissures extending through the turquoise are marked by a clearer fresh blue color along their margins. This relationship is quite the reverse of that which would be expected had the discoloration been introduced after the cutting and the burial; it seems likely that both the clearer places and the muddier tones were in the turquoise before it was cut.

The pyrite beads, on the other hand, have been strongly affected by the ground water which has penetrated the mound for six hundred years. The cord, of course, is long since gone, and the beads are now cemented together in a fragile jagged column. Here and there the brown crust has flaked away to reveal the inner core, which, wherever it can be seen, is fresh and shining pyrite. Rounded surfaces, with small, irregular etched elevations and depressions characterize the metallic mineral faces, none of the original polish noted on the turquoise is to be seen in these beads. The beads are all covered with a crust, which ranges from an almost paper thinness to 2 mm. thick, but very irregular in outline. This brownish crust of alteration contains two recognizable minerals and is the reason for this note.

First, and closest to the pyrite, are crusts and crystals of golden brown jarosite. Most of the crust is free from the pyrite, the jarosite masses being separated by a hair's breadth from the unaltered sulphide. Here and there however, a few isolated well-formed crystals of jarosite are growing on the pyrite itself. The pyrite beads have suffered badly from the alteration and are seamed and fissured so that no bead is intact, the altering solutions have worked in through the cracks and have produced jarosite which now cements the whole together, and which perhaps expanded the fissure as it formed.

The jarosite forms crystallized crusts up to half a millimeter in thickness, and grades down to single isolated crystals, perched upon the still brilliant pyrite surface. The free crystals show perfect combinations of *o* and *r*, and when viewed through the microscope, the combination of the upper and lower rhombohedral faces makes a golden six pointed star. The single crystals are exceedingly minute, some of the largest are but .025 mm. across and a little less in thickness. They are not isotropic in basal section, but show a typical abnormal segmental birefringence.

Outside of the jarosite there is a second compact crust composed of minute complex crystals of gypsum. Locally the crust is very solid and separated from the ochreous jarosite crust by a thin space into which the gypsum needles project. Elsewhere the crust is directly attached to the inner layer, and here and there a microscopic gypsum flower curls upward from its base.

No other distinct mineral was recognizable in the crusts. There was considerable adhering dust, presumably the dirt in which the skeleton lay, and around the jarosite there is some very fine-grained ochreous material. Probably a great part of this is also jarosite, some of it may be limonite developed from the jarosite with the release of sulphur.

The grave is dated about six hundred years ago; from this we can see that under the circumstances of alteration, jarosite must form very slowly and the pyrite oxidize slowly, to form such comparatively thin crusts in this span. Potassium and calcium have been introduced, the surrounding earth is the likely source of both these elements. Other than the limonitic dust here and there on the crust, there is no indication that jarosite has been replaced or altered. The gypsum may have formed from the excess sulphur released by the pyrite, or it may have formed after the jarosite, as a second alteration product. The occurrence is of interest not only because we can see a zoning of alteration products around the pyrite, but also because we have here a crust of measurable thickness, formed under known conditions, in a fixed period of time.

SKELETONIZED APOPHYLLITE FROM CRESTMORE AND RIVERSIDE, CALIFORNIA

Edgar H. Bailey, *Ontario, California.*

Skeletonized apophyllite is hydrous silica after apophyllite, which retains some of the physical and optical properties of the parent mineral, as well as its crystal form, and thus differs from merely pseudomorphic opal. Similar skeletonization has been demonstrated for other silicate minerals and also has been produced in the laboratory.

Recent blasting at Crestmore Commercial Quarry, the well known mineral locality three miles north of Riverside, California, has revealed snow-white tetragonal crystals up to 5 mm. long, associated with veins of colorless prehnite cutting garnet-diopside rock. Diligent search yielded only approximately 10 grams of the material with less than one gram of well-formed crystals.

A few of the crystals were found to have sufficiently smooth faces to give reflections which, though multiple and hazy, were good enough to measure on a one circle goniometer. The average of 12 measurements of (111) to $(11\bar{1})$ gave 119° 50′ as contrasted with 121° 04′ for apophyllite as given in *Dana's System.* A closer value of 119° 33′ was obtained by Luedecke (1) on apophyllite from Radauthal. The crystals have the habit of the apophyllite from Crestmore described by Eakle (2) with dominant pyramid {111}, generally subordinate prism {100} and very small, or absent, base {001}. No other forms were found on the Crestmore material.

The New City Quarry in the Victoria district of Riverside has yielded apophyllite crystals of cubo-octahedral habit up to 3 cm. in size. No prehnite was found with these crystals but late coatings of honey-colored calcite with dog-tooth habit are common. The crystals show bands or layers of pink, rather fibrous apophyllite alternating with much softer snow-white skeletonized apophyllite. One of the larger crystals contained a 1 cm. pseudocubic isotropic core of resin opal.

While the crystal forms are those of apophyllite and the basal cleavage is perfect, other physical properties of skeletonized apophyllite are markedly different. The hardness is about 1 and the mineral is extremely brittle. The color is dead snow-white, the luster is pearly on the basal pinacoid but dull on all other surfaces, and the crystals are not transparent.

Optical examination showed the skeletonized apophyllite to have variable properties. Thin sections indicated the maximum birefringence to be approximately .006, while minimum alpha obtained from crushed fragments was 1.439 and maximum gamma was 1.449. A uniaxial negative interference figure was given by many of the small plates.

Professor W. J. Crook of the Mining Department at Stanford University kindly made a spectroscopic study of the nearly pure mineral and reports: "The mineral appears to consist largely of silica and magnesia with small amounts of iron and manganese. Aluminum, copper, silver, titanium, and nickel are present in exceedingly small quantities."

An analysis for silica by the fusion method gave 88.54% and a Penfield test for water yielded 7.21%, indicating that the skeletonized apophyllite is hydrous silica (95.75%) with about 4% of magnesia, etc. A microchemical test for fluorine, following the method of Dr. L. W. Staples (3), gave negative results.

The chemical composition is similar to opal and as Eakle (2) has noted that the opal which coats apophyllite and okenite at Crestmore shows strong luminescence under the electric spark, the skeletonized apophyllite was examined under the iron arc. The associated coatings of hyalite opal glowed bright yellow and some skeletonized crystals showed almost as vivid a color, while other crystals failed to glow at all. The varied behavior of the crystals is probably due to the fact that in some cases microscopic films of secondary halite occur between basal plates of the skeletonized apophyllite.

The retention of some of the optical and physical properties of the parent mineral by the Crestmore and New City Quarry skeletonized apophyllite, suggests that the original apophyllite has undergone a selective leaching process in which calcium, fluorine, and potassium have been removed without destroying the silica framework of the crystals. However, a preliminary *x*-ray examination, using the powder method, failed to give any definite lines.

A search of the literature reveals that hydrous silica pseudomorphs after apophyllite have been found elsewhere. Schaller (4) reported quartz pseudomorphs after apophyllite from Fort Point, California, which were snow-white and opaque but did not yield optical properties. Chemical analysis showed them to contain 90.58% silica, 4.32% water, with the remaining 5% magnesia, lime, and alumina. The water content indicates that this may be skeletonized apophyllite rather than quartz. A. Scheit (5) found isotropic opal with index of 1.447 as pseudomorphs after apophyllite in the Böhmischen Mittelgebirge.

The skeletonization of other minerals has been reported previously. Rinne (6) described bauerite as the hydrous silica end-product formed by the baueritization of biotite, and retaining the optical properties of the original biotite. The term "baueritization" might be extended to apply to all cases where a silicate has been changed to silica with the partial retention of optical and physical properties. However, as the term has been used so often to mean the bleaching of biotite mica, it would seem wiser not to enlarge on the original definition.

The conversion of a silicate to a silica skeleton is readily brought about on some minerals in the laboratory by treating them with dilute acid. Smulikowski (7) has treated glauconite with acid which changes the mineral to a hydrated silica which is still optically negative and biaxial. On treating various zeolites with dilute HCl, Rinne (8) found that heulandite, brewsterite, and scolecite were converted to silica, but retained crystallographic angles and optical properties similar to those of the unaltered minerals. Chabazite and phillipsite, however, were converted to a silica gel. Apophyllite also is converted to a silica gel when treated with HCl according to *Dana's Textbook of Mineralogy.*

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NOTES ON FINAL GRINDING OF PETROGRAPHIC THIN SECTIONS

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Introduction

The final hand grinding of petrographic thin sections presents many difficulties and frequently many slides are ruined before the necessary technique is developed. The writer, after many unsuccessful attempts to consistently produce good slides, has noted two possible causes of failure: (1) insufficient observation of the progress of the grinding, and (2) curvature of the glass grinding plates. Although the remedial methods given here may be in use, the writer is not aware of mention of them in the literature.

Basically, the two remedies consist of (1) illuminating the glass grinding plate from below, and (2) producing the desired surface on the glass plate by hand grinding.

Illumination of the Glass Grinding Plate from Below

The reason for illuminating the glass grinding plate from below is the prevention of (1) wedging or beveling of the section, and (2) loss of parts of the section.

It is essential that profound wedging or beveling of the section be eliminated. Illumination from below reveals this wedging or beveling at an early stage, frequently before it could be observed otherwise. With dark rocks, the color of the section can be used to detect wedging, but with very light rocks a difference of 0.01 mm. is scarcely visible, by either reflected or transmitted light.

It is important to detect when loss of parts of the section occurs through wedging or breaking loose. The later is particularly important in soft rocks where crushing of the loose fragments cannot be felt through the fingertips.

With the larger sections the points of maximum grinding can also be seen by noting the thickness of the abrasive film under the section itself. Where the film is thinnest, grinding is most rapid, as can also be observed by watching the disappearance of a few pencil lines drawn across the ground rock surface, as grinding proceeds.

Although ground surfaces on the corners of the glass slide do no harm, they are not to be desired and furthermore indicate considerable tipping of the slide during grinding. A touching corner is quite apparent when illumination is from below.

To obtain illumination from below, the glass plate may be mounted as a top of a well in a table or as a part of the top of a box. In either case the plate should be mounted with its surface slightly higher than the surrounding wood and should fit snugly.

Adequate ventilation must be provided for as heat will cause rapid evaporation of the water from the mud on the plate. The choice of the correct amount of light will be determined by the dimensions of the box, and preliminary diffusion of the light is not particularly essential in that the ground glass surfaces of the plate itself accomplish this. If desired, however, an old grinding plate may be mounted inside, directly above the light, to aid in diffusion of the light, and to prevent excess heating of the upper plate.

A switch should be mounted on the outside as there are a few light gray slides in which loss of material can be seen best by illumination from above rather than below.

A large notch should be cut in the frame to facilitate removal of plates. It is best to establish some standard size for the plates and build the frame to fit, in order to aid in the replacement of plates.

LEVELING OF CURVED PLATES

Thick centers seem to be characteristic of slides cut by beginners. The causes of thicker centers than edges in slides are: (1) convex curvature of both surfaces of the section due to grinding on a curved plate, and (2) the natural tendency to tilt the slide and hence grind more on the edges than in the middle. Care will eliminate the later, but only a flat plate will eliminate the former.

A concave curvature of the surface of the grinding plate will usually result in a convex curvature of the section ground on that surface. The glass plates are usually curved slightly when bought, and become decidedly concave after moderate use. Although having the center of a plate 20 cm. wide 1 mm. lower than the edges may seem insignificant, it will make the surface ground on it convex to the extent of 0.01 mm. in a section 20 mm. wide. This causes quartz to be yellow in the center of the slide and white on the edges, greatly diminishing the value of the slide for study. This effect will be partially nullified by bending of the slide in grinding if the pressure is applied only to the center of the slide, but this does not remedy the basic cause.

There are two ways to detect curvature of a grinding plate. A good straight edge laid across the plate will reveal major curves, but lesser curves are not readily detected in this manner. A better method for the later is to observe the distortion of the reflection from the clean dry plate when it is held almost parallel with the line of sight. Looking thus at the reflection of the crossbars of a window is a particularly sensitive test.

In order to correct curvature, the plate should be fastened securely and rubbed with a carborundum stone or block of metal fed with abrasive. Grinding is rapid, and should be confined largely to the edges of the plate. When the surface is plane, fine abrasive should be used until smooth, for a rough surface will make section grinding too harsh and rapid.

Care should be taken to avoid making the plate convex, which will cause the centers of large slides to be ground away before the edges are "down."

A little time spent in regularly leveling the plates will increase the percentage of good slides considerably. Repeated replacement of worn plates with new glass is not very satisfactory because the "breaking in" of the new plates takes time and some glass is curved when bought.

NOMINATIONS FOR OFFICERS OF THE MINERALOGICAL SOCIETY OF AMERICA FOR 1942

The Council has nominated the following for officers of the Mineralogical Society of America for the year 1942:

PRESIDENT: Arthur F. Buddington, Princeton University, Princeton, New Jersey.
VICE-PRESIDENT: Martin J. Buerger, Mass. Inst. of Technology, Cambridge, Massachusetts.
SECRETARY: Paul F. Kerr, Columbia University, New York, N. Y.
TREASURER: Earl Ingerson, Geophysical Laboratory, Washington, D. C.
EDITOR: Walter F. Hunt, University of Michigan, Ann Arbor, Michigan.
COUNCILOR (1942–1945): Adolf Pabst, University of California, Berkeley, California.

ANNOUNCEMENT OF ANNUAL MEETING

The twenty-second annual meeting of the society will be held in Boston, Massachusetts, December 29–31, 1941, in connection with the 53rd meeting of the Geological Society of America.

Members of the society who are planning to present papers at the scientific sessions of the annual meeting should notify the secretary as soon as possible in order to receive the proper blanks for their abstracts. All abstracts should be in the secretary's office by *November 1.*

Advance announcement of the annual meeting will be distributed to members of the society, along with the ballot for officers, the middle of October. The final program of the meeting, including the schedule of papers, abstracts, and other information will be sent to each member in December. Further specific information regarding the annual meeting may be obtained from the secretary's office.

PAUL F. KERR, *Secretary*

Mr. Herbert P. Whitlock since 1918 curator of the Department of Minerals and Gems in the American Museum of Natural History, retired as head of the department on July 1. He will continue as Curator Emeritus of the Department of Geology and Mineralogy and Research Associate in Jade. His popular illustrated talks and annual public lectures on jade and jade carving will be continued. During Mr. Whitlock's tenure the collection of precious and semi-precious gems increased from 2,060 to 2,562 exhibits and the mineral collection from 18,452 to 21,293. The new, recently described mineral whitlockite, a tricalcium phosphate, has been named in his honor. Mr. Whitlock served as President of the mineralogist Society of America in 1933.

By the action of the Board of Trustees, Dr. Frederick H. Pough, formerly assistant curator of Geology and Mineralogy, became upon the retirement of Mr. Whitlock, acting curator of the Department of Minerals and Gems.

Dr. Frederick E. Wright of the Geophysical Laboratory of the Carnegie Institution of Washington was awarded the honorary degree of Doctor of Science at the commencement exercises of the University of Michigan, June 21, 1941.

BOOK REVIEW

DANA'S MANUAL OF MINERALOGY, revised by CORNELIUS S. HURLBUT, JR. Fifteenth edition. x+480 pages, 20 plates, 436 figures. John Wiley and Sons, Inc., New York; Chapman and Hall, Limited, London. **1941**. Price $4.00.

The fifteenth edition of the well known *Dana's Manual* has been in large part rewritten. The scope of the book remains the same, and some changes have been made by the author designed to make the book better suited as a textbook in elementary mineralogy. The page size has been increased to 6×9 inches, and the old flexible cover has been replaced by stiff cloth binding.

The contents are grouped into five major divisions: crystallography, physical mineralogy, chemical mineralogy, descriptive mineralogy, and determinative mineralogy. The subject of crystallography is simply presented. The symmetry elements explained and used are axis, plane, axis of rotary reflection, and center. The symmetry notations A_n, P, AP_n, and C are used. The crystal class names are those now in most general use, based on the names of the general forms (Groth-Rogers). A table lists all 32 crystal classes but only the 15 most important of these are discussed in the text. There are short discussions on twinning and crystal structure. No mention is made of the stereographic or gnomonic projections.

Part II, Physical Mineralogy, deals briefly with the physical properties of minerals. The book is not designed to be used as a text in optical crystallography.

Part III, Chemical Mineralogy, includes an excellent discussion of the relation of chemistry to crystallography. The confusion which has centered around the proper usage of the term "isomorphism" has been avoided by using the two terms isostructural and isomorphous. Directions for making blowpipe and chemical tests, and descriptions of tests for the elements constitute the bulk of Part III.

Part IV includes the description of 200 minerals. The mineral classification used is that which is being used in the new edition of Dana's *System of Mineralogy*, now in the process of preparation. Occurrence and uses of each mineral hold a prominent place in the descriptions. The mineral descriptions are followed by a general discussion of the occurrence and association of minerals, and this in turn by a section on mineral uses.

Part V consists of tables for the determination of minerals by their physical properties. Only common or economically important species have been included. Three different styles of type indicate the relative importance and frequency of occurrence of each mineral.

Two indexes are given, a subject index and a mineral index. The latter is an innovation and an extremely useful one. In the index, in tabular form after each mineral name is given composition, crystal system, specific gravity and hardness. Thus, to obtain any one of these facts about a particular mineral one need go no further than the index.

There are twenty plates (one a color plate) of unusually good photographs of mineral specimens. The crystal drawings are numerous and good.

The book is clearly and concisely written. It should serve excellently for the principal purpose for which it is designed, that of a text for an elementary course in mineralogy.

GEORGE SWITZER